MATERIALS OF CONSTRUCTION

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THEIR MANUFACTURE AND PROPERTIES

BY THE LATE
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OF CORNELL UNIVERSITY

SECOND, THIRD, AND FOURTH EDITIONS, EDITED BY
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FIFTH EDITION, REWRITTEN AND EDITED BY
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PREFACE TO THE FIFTH EDITION

The original purpose of Professor Mills of providing a textbook covering the manufacture, properties, and uses of the more common materials of engineering construction has been retained as the object in the preparation of the Fifth Edition. The changes in the Fifth Edition consist of the introduction of several new chapters on properties of materials and on the treatment of certain materials of construction not covered in previous editions, together with a revision of subject matter in all chapters and a rearrangement of the chapters.

The subject of fundamental properties of materials is treated, and methods of testing and requirements of metals in service are described. The fundamental properties of materials are defined in the first chapter so that the student may obtain in the beginning an understanding of the technical descriptive terms. A chapter on service requirements of metals discusses the subjects of slip, progressive fracture under repeated stresses, creep and the behavior of metals under high temperature conditions, impact testing, wear, and corrosion of metals.

More space has been devoted to the subject of metallography and the "constitution" of metals, which is a subject that is recognized to be of great importance to the engineer.

A short history of the development of metallurgical processes for ferrous metals is included. Additions and improvements have been made in the treatment of subjects such as the Aston process for manufacture of wrought iron, the malleablizing process for manufacturing malleable cast iron, manufacture and properties of ingot iron, welding, extraction of copper from its ores, and the properties and uses of non-ferrous metals and alloys (including die-casting metals and light-weight alloys), and of alloy steels.

The manufacture of Portland cement, its chemistry, and physical properties have been treated from a modern point of view. The work on concrete has been rewritten to present recognized theories of proportioning, modern methods of construction, and up-to-date values of physical properties.

Quarry and mill practice for building stone has been discussed. The descriptions of the manufacture of structural clay products have been revised to conform to modern practice. Glass building blocks have been briefly treated. The chapter on timber has been extended to include descriptions of defects and the action of termites and marine borers, and the tables of structural values have been improved.

A new chapter on bituminous materials has been included to meet the needs of engineers for a fundamental understanding of these important materials of construction.

One of the main additions to the Fifth Edition is the section on organic materials covering the subjects of protective coatings and organic plastics. The composition and selection of paint, varnish, and lacquer for different purposes are discussed. The properties and applications of a number of organic plastics are described.

The coöperation and assistance rendered to Professor Hayward in the preparation of the Second, Third, and Fourth Editions by the following members of the Massachusetts Institute of Technology faculty are acknowledged: Henry Fay, Robert S. Williams, Irving H. Cowdrey, George B. Haven, Dean Peabody, Jr., Ralph G. Adams, and Gordon B. Wilkes.

The author wishes to express his appreciation for the assistance which he has received in the preparation of this edition from the following individuals: Dean H. P. Hammond of the Pennsylvania State College for valuable suggestions and advice; Dr. C. L. Clark and Dr. R. Schneidewind of the University of Michigan and Professor O. H. Henry of the Polytechnic Institute of Brooklyn for valuable suggestions and contributed materials; Mr. F. R. McMillan, Director of Research, Portland Cement Association, for permission to reproduce figures and descriptions from his publications; and Dr. Wm. H. Gardner, Research Professor of Chemical Engineering, Polytechnic Institute of Brooklyn, for writing the chapters on organic protective coatings and organic plastics.

Acknowledgment is made to the following societies and organizations for permission to quote from their publications: American Society for Testing Materials, American Society of Civil Engineers, American Society of Mechanical Engineers, Society of Automotive Engineers, A. M. Byers Co., American Concrete Institute, Portland Cement Association, Vacuum Concrete Corporation, Forest Products Laboratory, Wm. F. Clapp Laboratory, Association of Asphalt Paving Technologists, and the Asphalt Institute.

LLOYD F. RADER

BROOKLYN, N. Y.
February, 1939.

PREFACE TO THE FIRST EDITION

This work is an outgrowth of certain lectures and notes which have been used in the author's classes in the College of Civil Engineering, Cornell University, for the past several years. Its preparation was undertaken to meet the need which was felt for a general textbook covering the manufacture, properties, and uses of the more common materials of engineering construction in a comparatively concise and thoroughly modern manner.

Although this book is intended primarily for use as a textbook of somewhat elementary character and is not a treatise exhaustively covering the very broad field of "Materials of Construction," the treatment has been made more detailed in some respects than may be necessary for class-room purposes, and its applications as a general reference work thereby broadened.

The treatment of the various classes of materials considered follows a general systematic form which has been made uniform throughout so far as has been found practicable. The consideration of each material or class of materials is prefaced by a discussion of its ordinary applications in engineering construction, followed by a study of its manufacture or natural occurrence, and concluded by a discussion of physical and mechanical properties in their relation to its uses.

As a result of the author's experience in the teaching of this subject, the properties exhibited by a given material are, for the most part, considered as dependent phenomena closely related to certain more or less variable factors connected with the process of manufacture, natural occurrence, and conditions of service or testing, and not as independent qualities inherent in that material. It has been considered advisable to avoid the inclusion of tabulations of investigational data whenever the data could be presented graphically by curves or diagrams; discussions of conflicting empirical data on points admitting of controversy have been reduced to a minimum; and an effort has been made to present the material in a definite, concrete form, the necessity for the exercise of discriminative judgment upon the part of the student being obviated by conclusions drawn by the author, even though it is recognized that in so doing errors of judgment may be made, and the criticism of those who object to any form of dogmatic statement is invited.

The subject of testing materials has not been covered, except in so far as methods of testing are inseparable from discussions of the properties of materials revealed by laboratory tests. It is the author's conviction that this subject can be handled only in the laboratory itself, and the place for such material is therefore in a laboratory manual. It is assumed, however, that a laboratory course in testing materials will invariably parallel and supplement the textbook course in the study of materials.

The author cannot make a pretense of being a specialist in all of the fields which are covered in the various chapters of this book, and this work is therefore to a very large degree a compilation of data and opinion from a great many different sources. The author takes pleasure in acknowledging his great indebtedness to the large number of engineers and manufacturers who have privately or by their writings contributed much to make up this volume. A large number of technical books which are devoted to the consideration of some part of the ground covered by this text have been frequently consulted and freely used. An effort has been made to always acknowledge the source of information so obtained, and if any error of omission has been committed in this respect, it has been committed inadvertently, not by intention.

The following well-known textbooks and reference works have been most frequently used:

"Cements, Limes, and Plasters," by E. C. Eckel; "Portland Cement," by R. K. Meade; "Manufacture of Portland Cement," by R. C. H. West; "Masonry Construction," by I. O. Baker; "Stone for Building and Decoration," by G. P. Merrill; "Building Stones and Clay Products" and "Economic Geology," by Heinrich Ries; "The Blast Furnace and the Manufacture of Pig Iron," by Robert Forsythe; "The Metallurgy of Iron and Steel," by Bradley Stoughton; "The Metallurgy of Steel" and "Iron, Steel, and Other Alloys," by H. M. Howe; "The Manufacture and Properties of Iron and Steel," by H. H. Campbell; "Iron and Steel," by H. P. Tiemann; "Modern Iron Foundry Practice," by G. R. Bale; "Cast Iron," by W. J. Keep; "The Production of Malleable Castings," by Richard Moldenke; "The Corrosion and Preservation of Iron and Steel," by A. S. Cushman and H. A. Gardner; "The Metallography of Iron and Steel," by Albert Sauveur; and "Economic Woods of the United States" and "The Mechanical Properties of Wood," by S. J. Record.

The following periodicals and publications of various societies have also been frequently consulted:

"Engineering News," "Engineering Record," "Metallurgical and Chemical Engineering," Proceedings of the American Society for Testing Materials, Proceedings of the International Association for Testing Materials, Transactions of the American Society of Civil Engineers, Proceedings of the Institution of Mechanical Engineers, Journal of the Iron and Steel Institute, "Tests of Metals," published annually by the U. S. War Department, "Mineral Resources," published annually by the U. S. Geological Survey, Reports of the various State Geological Surveys, the publications of the Forestry Division of the U. S. Department of Agriculture, and the publications of the U. S. Bureau of Standards.

ADELBERT P. MILLS

ITHACA, N. Y.
February 20, 1915.

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MATERIALS OF CONSTRUCTION

SECTION 1

DEFINITIONS OF TERMS

CHAPTER I

DEFINITIONS OF TERMS

By Lloyd F. Rader *

1. Introduction. The study of materials of construction is of great importance in all branches of engineering. The common materials of engineering construction are treated in this volume from the standpoint of occurrence and manufacture, properties, uses, and testing methods.

Definitions of terms relating to properties of materials and methods of testing are given in this first chapter.

2. Stress and Strain. **Stress* † is the intensity of the internal distributed forces or components of force which resist a change in the form of a body. Stress is measured in units of force per unit area (pounds per square inch, kilograms per square millimeter, etc.).

In many American engineering textbooks the term stress is defined as a force, measured in pounds, as for example the use of the term stress in the "stress sheet" of the structural engineer which gives forces. The term "unit stress" may be employed to indicate that the term is used to denote force per unit of area.

There are three kinds of stress: tensile, compressive, and shearing. Flexure involves the combination of tensile stress and compressive stress. Torsion involves shearing stress.

* *Tensile strength* is the maximum tensile stress which a material is capable of developing. It is computed by dividing the maximum load carried during a tension test by the original cross-sectional area of the specimen.

* *Compressive strength* is the maximum compressive stress which a material is capable of developing.

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† Definitions marked by an asterisk are from the Standard Definitions of Terms Relating to Methods of Testing, A.S.T.M. Designation: E 6–36.

Shear strength is the maximum shear stress which a material is capable of developing.

* *Strain* or *deformation* is the change, per unit of length, in a linear dimension of a body, which accompanies a stress. Strain is measured in inches per inch of length (feet per foot, millimeters per millimeter, etc.)

In many American engineering textbooks the term "strain" is used in the sense of total deformation and is measured in inches; change of dimension per unit length is called "unit strain" or "unit deformation."

* A *stress-strain diagram* is a diagram plotted with values of stress as ordinates and values of strain as abscissas. (See Fig. 1.)

* *Elastic limit* is the greatest stress which a material is capable of developing without a permanent deformation remaining upon complete release of stress.

* *Proportional limit* is the greatest stress which a material is capable of developing without a deviation from the law of proportionality of stress to strain (Hooke's law). Point A in Fig. 1 is the proportional limit. For many metallic materials the values found for elastic limit by means of observations of permanent deformation after release of stress do not differ widely from the values found for proportional limit.

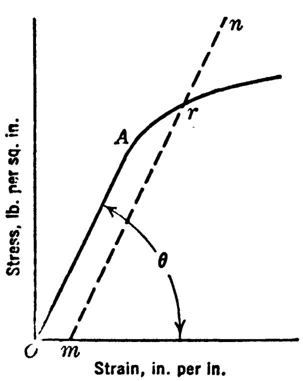

Fig. 1.—Stress-strain Diagram.

* *Yield point* is the stress in a material at which there occurs a marked increase in strain without an increase in stress. The yield point defines the stress beyond which structural damage is likely to occur. Ductile irons and steels and a few non-ferrous metals have well-defined yield points. (See Fig. 3.) The yield point may be readily determined by the "drop of beam" method in the tension test.

Most metals do not have well-defined yield points, but have smooth stress-strain curves of gradual curvature in the yield range. Therefore, some other method must be employed to determine the limiting stress above which structural damage is likely to occur. The method of yield strength is recommended by the American Society for Testing Materials to meet this requirement.

* *Yield strength* is the stress at which a material exhibits a specified limiting permanent set. The specified value of the permanent set is laid off as Om on the stress-strain diagram (Fig. 1). The line mn is drawn parallel to the straight part of the stress-strain diagram OA. The intersection of mn with the stress-strain diagram at point r gives the stress

which is the yield strength. The specified value of the offset in per cent should be reported.

3. Elasticity. *Elasticity* is that property of matter by which a body, if deformed by the action of forces, will endeavor to resume its original shape when the disturbing forces are removed. The elasticity of a number of engineering materials is practically perfect provided that they are not stressed above the elastic limit.

Hooke's law states that in elastic bodies stress is proportional to strain provided that the elastic limit is not exceeded. Most materials show slight variations from Hooke's law, but the common metals adhere to it so closely as to justify its assumption from a practical standpoint.

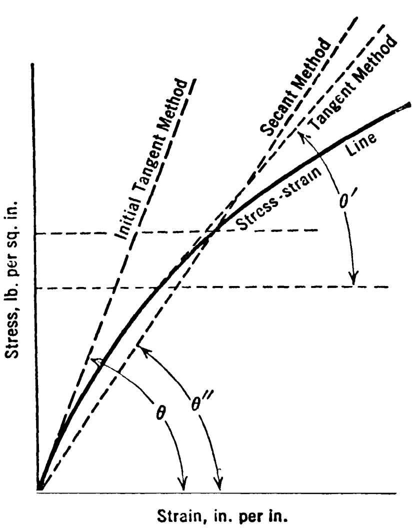

FIG. 2.—Three Methods of Determining Modulus of Elasticity of a Material Having a Curved Stress-strain Diagram.

4. Modulus of Elasticity. *Modulus of elasticity* is the ratio, within the elastic limit of a material, of stress to corresponding strain. It is a measure of the *stiffness* of a material. Modulus of elasticity is expressed in pounds per square inch. As there are three kinds of stress, so are there three moduli of elasticity for any elastic material: the modulus in tension, in compression, and in shear.

The modulus of elasticity in tension has nearly the same value, for most metals, as the modulus of elasticity in compression. The modulus of elasticity in shear is smaller than the modulus of elasticity in tension. The modulus of elasticity in shear may be determined by means of a torsional test. The modulus of elasticity in flexure can also be obtained in connection with the flexure test. The modulus of elasticity is the slope of the stress-strain curve within the elastic range, i.e., $E = \tan \theta$ (Fig. 1).

Strictly speaking, the modulus of elasticity should be considered only within the range where the stress-strain relation is practically constant for materials of a truly elastic nature. It is common practice, however, to determine the modulus of elasticity for materials whose stress-strain graph is a curved line and whose elastic limit is relatively low in value, as, for example, concrete. The modulus of elasticity for such materials is determined by an arbitrary method. Three such methods in common use are illustrated in Fig. 2: (1) the initial tangent method, (2) the tangent method, and (3) the secant method. Suitable stresses are chosen in the tangent and in the secant method. The values of E for each method may be determined by finding the tangents of the angles θ, θ', and θ'' respectively.

5. Physical Properties of Materials. *Resilience* is that property of an elastic body by which energy can be stored up in the body by loads applied to it and given up in recovering its original shape when the loads are removed.

Plasticity is the property by which a body, when deformed by the application of forces, remains in the deformed shape without recovering its original shape when the forces are removed. Some materials are partly elastic and partly plastic since they recover a part of the deformation when the load is removed. Some metals become partly plastic at elevated temperatures. Materials stressed above the elastic limit so as to produce some permanent set are partly plastic. Plasticity of metals is usually determined by means of a tensile-strength test.

Ductility is the property of a material of being deformed by stretching, without recovery of shape upon removal of the stretching force. Ductility of metals is ordinarily determined by measuring the elongation and reduction of cross-sectional area of a tensile-strength-test specimen.

Malleability refers to the ability of a material to withstand hammering into a thinner sheet without fracture. It depends on the ductility and softness of the material.

Hardness is resistance to plastic deformation. Thus a hard material may have a high elastic limit or a high value of stress below which there is no permanent set. Other meanings are given to the term, however, such as resistance (1) to abrasion, (2) to scratching, or (3) to indentation of a cone or ball.

Toughness may be defined as resistance to impact. Toughness is also considered to mean resistance to fracture when the material is deformed above the elastic limit. A tough material can withstand appreciable permanent deformation before fracturing.

Brittleness is the opposite of toughness and ductility and refers to small resistance to a sudden blow. A brittle metal breaks suddenly without appreciable permanent deformation or warning of approaching failure.

Durability refers to resistance of a material to deterioration in quality during its period of use.

6. Stress-concentration Factor. The term "stress-concentration factor" may be defined as the ratio between the stress actually occurring at a section of localized stress (such as at a notch, at the edge of a hole, at the root of a screw thread, at a shoulder in a shaft, or other sudden change in cross-section) and the stress at that point as calculated by the formulas of mechanics of materials.

7. Statistical Properties of Materials. The subject of mechanics of materials which is based on Newtonian mechanics implies definite relations in the physical world between cause and effect. That these relations may be predicted only on the basis of probability is the viewpoint of modern physics. These probabilities when considered in terms of a great number of atoms become exact laws in the same sense that actuarial tables of life insurance based upon the records of many persons are exact. The results obtained by the application of these laws of probability to an individual case may differ greatly from the actual value. Or if only a small section of material is considered as, for example, the material near a small notch, the probable stress calculated by mechanics may not agree with the actual stress. But if the section of material is large enough so that it contains almost an infinitude of atoms, there are many paths through which action may take place and the most probable or "statistical" value should be close to the actual value.

The engineer in dealing with the properties of materials should keep in mind that natural phenomena just happen and that there is no controlling law which predicts the details of that occurrence exactly. Any physical phenomenon which may be observed is controlled by chance, and prediction may be made only in terms of probability or statistically. Furthermore, mechanics of materials formulas are based on the supposition that the material is homogeneous, isotropic, and elastic, and that it satisfies Hooke's law; although most materials of construction satisfy these assumptions closely enough for most practical purposes, stresses and strains calculated by mechanics of materials formulas are in reality only statistical approximations.

QUESTIONS

1. Define the following terms: stress, strain, deformation, elastic limit, proportional limit, yield point, and yield strength.
2. What is the significance of the modulus of elasticity?
3. Distinguish between elasticity and plasticity.
4. Define: ductility, malleability, toughness, and brittleness.
5. State four different meanings given to the term "hardness."

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SECTION 2

METALS

CHAPTER II

TESTS OF METALS

By Lloyd F. Rader

8. Purpose of Physical Tests of Materials. Physical tests are conducted on materials of construction in order to determine their quality and their suitability for specific uses in machines and structures. It is necessary for both the consumer and the producer to have tests for determining quantitative properties of materials in order that materials may be properly selected and specified. Tests are also needed to duplicate materials and to check up on the uniformity of different shipments. In fact, in describing materials of construction, quantitative data obtained by testing are necessary in order to describe adequately the properties of materials produced from different raw materials and by different processes.

9. Physical Tests of Metals. Tests commonly employed in determining the physical properties of metals include: tension, ductility, compression, flexure, torsion, hardness, endurance to repeated stresses or fatigue, and impact tests. These methods of testing pertaining to metals are briefly described in this chapter, but the values of physical properties of metals are given in the chapters pertaining to the different metals. The service requirements of metals as measured by resistance to repeated stresses (fatigue), creep, impact, wear, and corrosion are discussed in more detail in Chapter XII at the end of Section 2 on Metals.

10. Physical Tests of Non-metallic Materials. Common physical tests of non-metallic materials of construction such as mortar, concrete, building stone, structural clay products, and timber include compression, tension, and flexure tests. Endurance to repeated stresses or fatigue, resistance to abrasion, resistance to impact, and permeability are determined in special cases. The methods of testing each non-metallic material are described and typical test values are given in the chapters on the various materials.

11. Tensile-strength Test. Most commercial specifications for metals have requirements for physical properties as determined by the tensile-strength test. The properties determined include ultimate tensile strength, yield strength or yield point, elongation, character of fracture, and reduction of area. In order to obtain complete information concerning the tensile properties of a metal, a stress-strain curve should be determined experimentally. Strains corresponding to definite stresses imposed upon the specimen are measured by means of an extensometer. The extensometer is attached to the specimen so as to measure elongations between two gauge points. The procedure may consist of taking a series of load readings on the testing machine with corresponding readings of the extensometer, or the stress-strain diagram may be drawn directly by an autographic attachment to the testing machine.

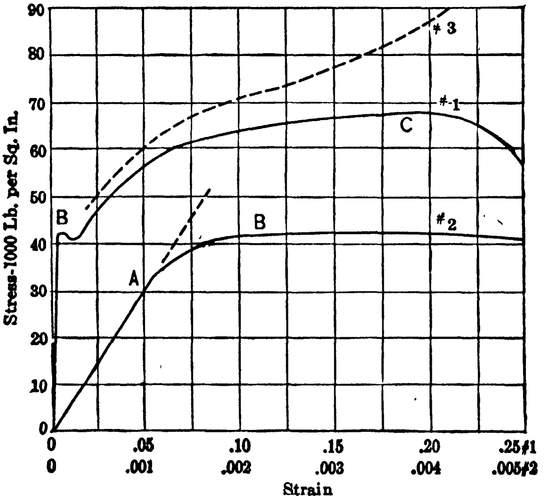

FIG. 3.—Stress-strain Curves for Mild Steel.

For metals having no well-defined yield point (Fig. 1), the yield strength is ordinarily determined, as explained in Art. 2. Ductile carbon steel has a well-defined yield point. Owing to the importance of steel, the methods of testing steel in tension are described in some detail in the following articles.

12. The General Behavior of Steel under Tensile Stress. The behavior of steel under tensile stress is best studied with the aid of the *stress-strain* diagram. Curve 1 of Fig. 3 presents a typical stress-strain diagram for a mild steel. Curve 2 shows the portion of curve 1 between *O* and *B* to an enlarged horizontal scale. This second curve to such a scale is necessary in order that the *limit of proportionality* or the point of departure of the curve from the straight line at *A* can be accurately located. For steel the elastic limit and proportional limit are usually considered to be identical. The *yield point B* is easily detected either by making a test (by the drop of the weighing lever or halt of the gauge of the testing machine), or from the stress-strain diagram where a more or less sharp break appears in the curve when the yield point is reached. The *ultimate strength* is represented by the maximum ordinate to the stress-strain curve at *C*.

The stress-strain diagram for steel in compression is essentially similar to the curve as described for tension, and the elastic limit is approximately the same in both cases.

The modulus of elasticity can be determined from the slope of the first portion of the stress-strain diagram, but is usually computed from the observed values of stress and strain. The modulus of elasticity is unaffected by the factors which influence other properties of steels and is about 29,000,000 pounds per square inch for practically any class of carbon steel.

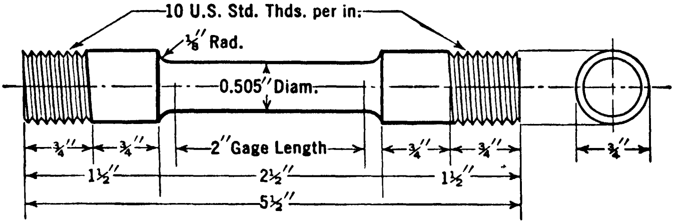

FIG. 4.—Standard Tensile-strength Test Specimen.

13. Routine Commercial Tension Test of Steel. In this test the ultimate tensile strength, the yield point, the per cent elongation, and the character of the fracture are determined. Sometimes the per cent reduction of area is also determined. The standard tensile-test specimen, shown in Fig. 4, has a diameter of 0.505 inch and a cross-sectional area of 0.2 square inch.

All these values can be obtained by a single operator. It is not customary to determine deformations of the specimen for plotting the stress-strain curve in the routine commercial tension test of ductile carbon steel since a great deal of additional labor and cost would be required.

Ultimate Tensile Strength. This value is determined by dividing the maximum load registered on the testing machine by the nominal cross-sectional area of the specimen. Maximum load occurs simultaneously with the beginning of the "necking down" in ductile steel and with rupture in brittle materials.

Yield Point. Yield point is usually obtained on ductile carbon steel by the drop-of-the-beam method which consists of reading the load on the weighing beam of the testing machine when the beam drops as the load on the specimen decreases just after the yield point is reached. This load divided by nominal cross-sectional area is the yield point. Care should be taken to apply the load at a low rate when approaching the yield point, and the poise on the weighing beam should be moved carefully to keep the beam in balance in order to secure accurate results.

As an aid in determining the yield point, a divider pointer may be inserted in the gauge marks of the specimen for the purpose of indicating the large deformations which occur after the yield point is reached. Frequently the loosening of scale on the steel specimen indicates these large deformations.

Elongation. Elongation of the specimen after fracture may be determined by placing the parts of the broken specimen closely together and holding them in place by means of a vise. The distance between gauge marks may be measured to the nearest 0.01 inch by means of dividers.

$$\text{Per cent elongation} = \frac{\text{Final length} - \text{Original length}}{\text{Original length}} \times 100$$

Character of the Fracture. Valuable information concerning the characteristics and composition of metals may be obtained by observing the character of the fracture of the test specimens. Necking down of the cross-section of the specimen near the fracture accompanied by a fracture in the form of a cup and cone indicates ductility and is typical of low-carbon steel. A square break normal to the longitudinal axis with little or no necking down indicates a non-ductile metal such as high-carbon steel or gray cast iron.

The texture of the metal at the fracture is commonly recorded. The texture of low-carbon steel is usually "silky"; in high-carbon steel, finely crystalline; in cast iron, finely or coarsely crystalline. By observing the extent of necking down and the type and texture of the fracture, the carbon content of steels can be estimated approximately.

A rosette or serrated fracture is typical of heat-treated high-strength alloy steel. Many non-ferrous metals exhibit considerable elongation over the length of the specimen without appreciable necking down. Wrought iron may be distinguished by the fibrous structure of its fracture.

Reduction of Area. Reduction of area can usually be determined if the specimen is circular in cross-section. The area of the smallest cross-section after fracture may be measured by means of thin pointed calipers to the nearest 0.01 inch. If the section is slightly irregular, the maximum and minimum diameters may be measured and the cross-sectional area computed as a circle, taking the mean of the observed values as diameter. Such an irregular section may be computed as an ellipse.

It is difficult to measure the cross-sectional area of rectangular sections when fractured since necking down tends to produce a section composed of four concave surfaces. The cross-sectional area of deformed reinforcing bars is also difficult to determine. Reduction of area is ordinarily not reported for such specimens.

$$\text{Per cent reduction of area} = \frac{\text{Original area} - \text{Area after fracture}}{\text{Original area}} \times 100$$

14. Distribution of Elongation. The distribution of elongation of a steel specimen in tension is illustrated by Fig. 5. If uninfluenced by any local cause, a bar of homogeneous steel subjected to axial tension should fail near the center of the distance between the points of application of the load, because there the flow of the metal will be least impeded. The maximum ordinate to the curve of Fig. 5 represents the point where necking down occurred, since the point of maximum reduction in area must necessarily coincide with the point of maximum elongation. The fact that steel test specimens are reduced in cross-section as they are elongated under stress, and finally neck down, accounts for the fact that the breaking load, according to the stress-strain diagram, is below the ultimate strength. If the stress at all loads was computed upon the basis of the actual section then existing, instead of being computed (as it always is) upon the basis of the original section, the stress-strain curve would follow such a course as is indicated by the dotted-line curve 3 of Fig. 3.

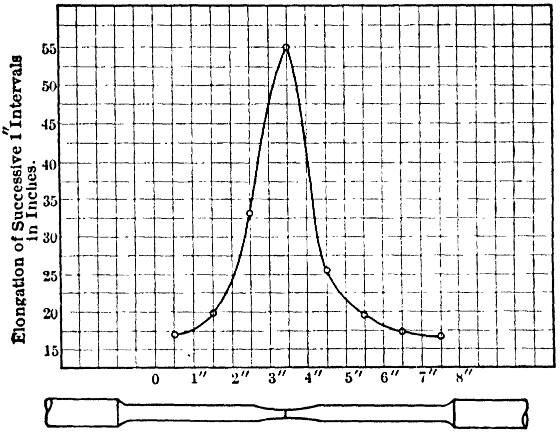

FIG. 5.—Distribution of Elongation.

The marked effect of gauged length upon percentage elongation is shown by the series of curves plotted in Fig. 6, which are based upon a series of tests of open-hearth steel made by Mills. These tests were made upon 1-inch round bars 8 feet long, gauge points having been marked at 1-inch intervals along the entire length of each specimen. Each of the gauged lengths over which measurements were taken after fracture included the fracture and necked-down portion at the center, or within ½ inch of the center.

The percentages of elongation and reduction of area, as found for specimens of different diameters, are comparable only when the specimens are geometrically similar. The original gauged length should always be reported in connection with elongation.

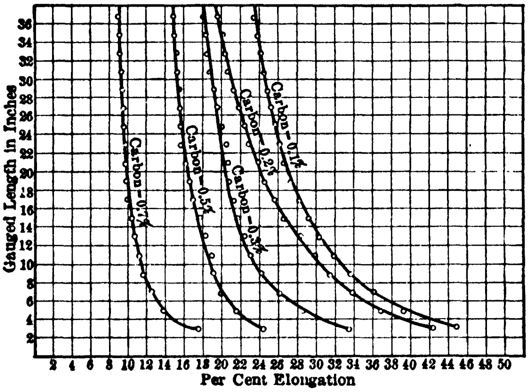

Fig. 6.—Effect of Gauged Length on Per Cent Elongation.

15. Ductility Testing. Ductility of metals is usually determined in the tension test by noting the percentage elongation and in some cases the percentage reduction of area.

The indication of the ductility of steel which is afforded by a simple *cold-bending test* is also very valuable and significant. Cold-bending is accomplished either in a special bending machine or by blows or pressure. According to the severity of the test desired, the bend may be made over a sharp edge, or about a pin or template of any desired radius.

The *drift test* is used to determine ductility of metal plates. A hole of a given size is bored into the metal plate and expanded by driving a drift pin into it until the metal is fractured. The ratio of sizes of holes before and after the test is a measure of ductility.

16. Compressive Strength. The compressive strength should be determined on cylinders with a height equal to about two times the diameter. The ends of the cylinders should be carefully prepared to insure parallel and plane surfaces. Load should be applied concentrically, using spherical-seated bearing blocks.

For steels it is possible to determine the ultimate compressive strength only for brittle steels since all ductile steels are greatly deformed under load and show no well-defined fracture.

The compressive strength of metal is quite closely allied with the tensile strength, the properties revealed under one kind of stress being practically identical with those revealed under the opposite kind. It is not necessary, therefore, to consider tensile strength and compressive strength separately, except to a slight extent. One fact which must not be overlooked in this connection is that soft or medium steel is often subjected to compressive loading under such circumstances that the stress induced does not remain purely compressive, but becomes a combination of compressive stress with bending stresses. The behavior of the material in this event is manifestly not that which is characteristic of steel in compression. When, for instance, compressive load is applied to a steel test specimen whose length is more than three or four times its diameter, or to a steel column whose length bears a large ratio to the least radius of gyration of its cross-section, complete failure occurs under a load which has induced an average compressive stress only slightly in excess of the yield point. Flow of the ductile metal at the yield point has caused eccentricity of stress, and failure ensues almost immediately owing to lateral flexure and the concentration of stress in the extreme fiber on one side of the section.

17. Flexural Strength. In the flexure test, the beam may be tested on simple supports or as cantilevers with one end fixed. The flexural strength is commonly expressed by the term "modulus of rupture," meaning the apparent extreme fiber stress under the load which produces rupture as computed from the flexure formula,

$$f = My \div I$$

wherein f is the extreme fiber stress, M is the bending moment, y is the distance from the neutral axis to the extreme fiber, and I is the moment of inertia of the section.

As a matter of mechanics, this procedure is not warranted, since it involves the assumption that the neutral axis remains a constant distance from the extreme fiber, and the further assumption that a constant proportionality of strain to stress obtains for all stresses up to the breaking stress.

The proportion of strain to stress is not a constant, and the neutral axis shifts as the material deforms. Therefore the actual extreme fiber stress is less than this value of f computed by the rule for the bending moment which exists under the load which produces rupture, and, indeed, the actual fiber stress for cast iron is not more than 50 to 60 per cent of the modulus of rupture.

The modulus of rupture, however, is a good index for comparing different grades and classes of materials. The beams tested in flexure in a given series of tests should be of the same shape and size so that the modulus-of-rupture values can be compared directly.

The flexural strength of a metal is directly dependent upon the tensile and compressive properties of that metal. Whether one or the other is the controlling factor is dependent upon the form of the beam and the location of the neutral axis. If the section is symmetrical the failure will usually occur on the tension side if the metal is not ductile, and on the compression side if it is ductile. Absolute rupture in cross-bending is not possible with any grade of mild or medium steel, since these steels may be bent 180 degrees without fracture.

The modulus of elasticity as obtained from bending tests is slightly lower than the values obtained from tensile or compression tests because the slight deflection due to the shear introduces a small error into the formulas for deflection from which the flexural modulus of elasticity is usually calculated.

18. Torsion Test. The torsion test is conducted by twisting a solid cylindrical specimen. The torque and the angle of twist are measured.

The intensity of the shearing stress due to torsion on any section of a cylindrical shaft is not uniform, but varies directly as the distance from the axis of the shaft (assuming that the section is circular), and the maximum intensity of shearing stress is therefore found at the circumference. The mathematical expression for the maximum shearing stress in the extreme fiber of circular shafts is:

$$s = \frac{2\,Pa}{\pi r^3}$$

where Pa is the torque, r is the radius of the section, and s the shearing stress in the extreme fiber of the shaft.

The shearing modulus of elasticity E_s is expressed by the equation

$$E_s = \frac{sl}{r\theta}$$

where l is the distance between the planes of the external forces, and θ is the angle of torque or twist.

The shearing strength as determined by torsion tests appears higher than it does in the case of direct shear. This is because the expression for s above is true only as long as the material behaves elastically. When computed for the torque which produces rupture it may be called the "torsional modulus of rupture" and corresponds to the true value of the shearing strength of the material in about the same way as the modulus of rupture for cross-breaking corresponds to the actual extreme fiber stress.

19. Hardness Tests of Metals. Hardness of metals is usually determined by measuring the resistance to penetration of a ball, cone, or pyramid.

The *Brinell* method is based upon determining the resistance offered to indentation by a hardened sphere which is subjected to a given pressure. The pressure used in testing steel is usually 3000 kilograms, and the diameter of the ball is 10 millimeters. When testing softer materials a pressure of 500 kilograms is used. Brinell numbers can be computed by the formula

$$\text{BHN} = \frac{2P}{\pi D\ (D - \sqrt{D^2 - d^2})}$$

where P is pressure in kilograms; D and d, respectively, the diameters of the ball and of the impression in millimeters.

The *Rockwell* method is also a ball-indentation method used in determining hardness. Two superimposed impressions are made, one with a load of 10 kilograms and the second with a load of 100 kilograms. The depth to which the major load drives the ball below that to which the minor load has previously driven it is taken as a measure of the hardness. The size of the ball generally used is $\frac{1}{16}$ inch in diameter, but for hardened steels greater accuracy is obtained by use of a diamond cone (120 degrees with slightly rounded tip) applied under a major load of 150 kilograms. The regular test is called Rockwell "C" hardness.

Tests conducted at the Massachusetts Institute of Technology indicate the relations between the Brinell and the Rockwell hardness scales as shown in Fig. 7.

The *Vickers* method is a plastic indentation method similar to the Brinell but uses a square diamond pyramid as an indentor which eliminates the errors due to deformation of the steel ball and places practically no limits on the hardness of metals that can be accurately determined. The impressions may be small and shallow owing to the fact that light pressures may be employed, making it possible to determine, satisfactorily, the hardness of fairly thin material and to test finished work without serious injury. The values obtained approximate those obtained by the Brinell apparatus, but are not subject to the variations in accuracy of that method.

The *Shore scleroscope test* is made by means of a pointed hammer which is allowed to fall through a guiding glass tube upon the metal being tested. The hardness is expressed by the height of rebound of the hammer after falling from a specified height. The hammer of the instrument becomes slightly changed in form after a certain number of tests and must then be recalibrated. The indications of the instrument must certainly be dependent in some measure upon the resiliency of the material tested as well as that of the hammer itself, but the extent of the permanent deformation of the metal is also a factor. For ordinary steels the Brinell number is approximately the scleroscope number multiplied by 5¾ to 6¼.

The *cone test*, first proposed by Ludwick, is the same in principle as the Brinell test, but a hardened-steel cone of 90-degree angular opening is substituted for the steel sphere. The cone test fails on very hard steel because of the flattening of the point of the cone under the heavy pressure required.

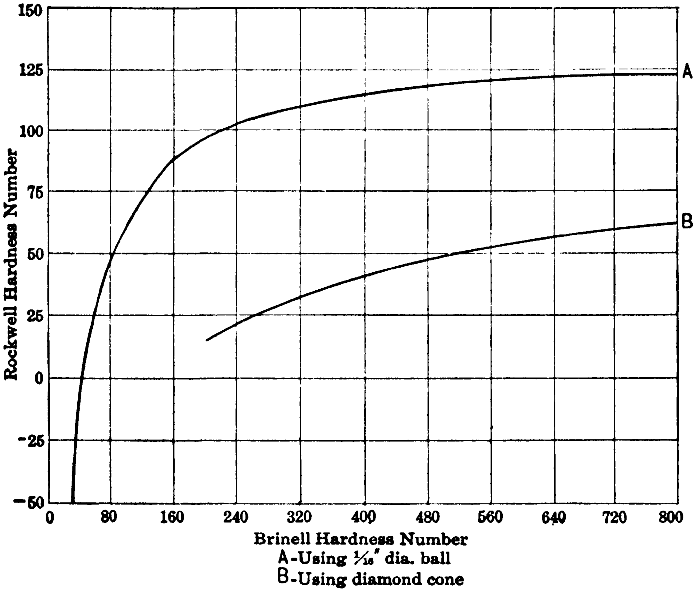

FIG. 7.—Relation between Rockwell and Brinell Hardness Scales. (Curve B refers to Rockwell "C" Hardness.)

The *Bauer drill test* is made by means of a special drill driven at constant speed, with a fixed pressure of the drill, upon the specimen of steel. The hardness is measured by the depth of the hole drilled with a given number of revolutions, the pressure remaining constant. This test is, of course, simply a measure of the resistance offered to cutting.

The *Herbert test* for hardness, as recently developed, operates on a different principle. A heavy balanced pendulum rests, through a small steel or diamond ball, on a leveled surface of the material to be tested, and the amplitude or the period of the swing of the pendulum after starting from a given position is taken as the Herbert hardness number.

Tests of the resistance of steel to wear caused by dry rolling friction have been made, but the results of such tests do not agree very closely with the hardness determination made by other methods since the resistance of a material to wear is a quite different property from its resistance to indentation or its resiliency.

The hardness test is finding a constantly widening field of application. It can be used to test castings, forgings, etc., without impairing their subsequent availability for use. It can also be used advantageously in exploring different portions of a finished article to ascertain the varying effect of cooling conditions, working, etc., upon the properties of the metal.

20. Fatigue Tests. Fatigue tests, or tests to determine endurance to repeated stresses, are commonly conducted on metals by means of a rotating beam machine such as the R. R. Moore machine in which bending moment is applied to the specimen through holders at operating speeds of 1725 and 3450 cycles per minute. This apparatus produces alternating or *reversed stress* where stress in the specimen changes from tension to compression with each half revolution.

Some fatigue-testing machines produce stress of only one type, either tensile or compressive, which is termed *swelling stress. Repeated stress* is a general term including both this type and reversed stress.

The *endurance limit* is usually determined in fatigue testing. This is the stress below which a material can withstand an indefinitely large number of repetitions of stress without failure. It is determined by testing specimens for a number of cycles of stress of different magnitudes.

The behavior of metals under repeated stress is discussed in more detail in Chapter XII.

21. Impact Tests. Impact tests may be performed for two purposes: (1) to determine the ability of the material to resist impact under service conditions, and (2) to determine the quality of the metal from a metallurgical standpoint. Impact tests may be classified into two groups: (1) utility impact tests, and (2) standard impact tests.

Utility Impact Tests. Utility impact tests for detecting the presence of brittleness or determining the comparative toughness of materials are applied to steel rails, pipes, tubing, gear teeth, and tire chains, as well as to non-metallic materials such as concrete, stone, wood, fiber board, bituminous paving mixtures, enamels, and organic plastics. Such tests are conducted with machines and specimens of various types, shapes, and sizes.

Standard Impact Tests. The Charpy and the Izod impact-testing machines are the two most common machines for conducting standard impact tests on metals. These machines determine the amount of work in foot-pounds necessary to fracture a small test specimen by impact. They consist essentially of a weighted pendulum, suitable holders or supports for the specimen, and a device for recording the angular swing of the pendulum. The work done in fracturing the specimen must be absorbed from the energy of the swinging pendulum. Consequently, the pendulum rises to a smaller angle than it would for a free swing. The energy absorbed by the specimen may be computed from the angle to which the pendulum actually rises after fracturing the specimen.

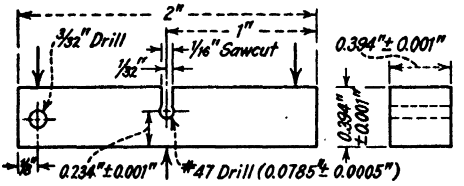

Fig. 8.—Charpy Transverse Type Impact Specimen. Saw cut must not strike side or bottom of drilled hole.

The specimens tested are generally notched in order to secure uniformity of results by localization of the fracture. Either tensile or transverse type specimens can be tested in the Charpy machine. The transverse type shown in Fig. 8 is well adapted for examining metals which break with a relatively low absorption of energy, since the notch is not sufficiently sharp to make the spread of foot-pound values too narrow. The depth of the notch eliminates the influence of surface effects. For tough metals the notched Izod type of specimen tested as a cantilever is frequently used. (See Fig. 9.) For extremely brittle metal the test specimen requires no notch because the first suddenly applied stress causes a brittle failure.

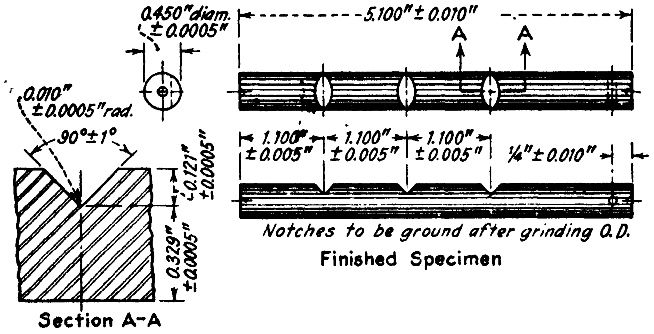

Fig. 9.—Izod Cantilever Type Impact Specimen.

Impact tests are not limited in application to metals that are to be subjected to impact in service but are also employed to determine whether metals are metallurgically satisfactory. The theory of impact tests and their use in selection of metals are described in Chapter XII.

QUESTIONS

1. Draw a stress-strain diagram for structural steel showing thereon approximate average values of yield point, proportional limit, ultimate strength, and modulus of elasticity.

2. Name and briefly describe the principal observations made in the routine commercial tension test of structural steel. Which of these observations are indications of the ductility of the steel? Briefly describe the form of a test specimen commonly used in this test.

3. What effect has the gauge length upon the percentage elongation found in the commercial tension test? What gauge length is usually specified?

4. For what purpose is an extensometer test conducted on a specimen of structural steel?

5. What is meant by a "cup and cone" fracture?

6. What is the purpose of the cold-bend test of steel? of the drift test?

7. Why should beams of a given material tested in flexure be of the same dimensions?

8. Describe the torsion test of metal.

9. Describe how the hardness of steels is determined by various methods.

10. For what purposes may impact tests be conducted on metals?

11. Compare the Charpy and Izod impact-test specimens.

12. Describe briefly the testing of metals in fatigue.

13. The results of a tension test on a specimen of high-carbon steel 0.505 inch in diameter is given as follows:

LOAD, LB.	TOTAL ELONGATION IN 2 IN., IN.
1,990	0.0007
4,005	0.0013
6,010	0.0020
8,120	0.0027
10,250	0.0034
11,780	0.0039
14,230	0.0047
15,620	0.0053
16,150	0.0056
16,700	0.0110
17,840	0.0171

Determine the yield strength for an offset of 0.2 per cent, and compute the value of the modulus of elasticity.

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CHAPTER III

STRUCTURE AND CONSTITUTION OF METALS

ORIGINALLY WRITTEN BY ROBERT S. WILLIAMS *

REWRITTEN BY LLOYD F. RADER

22. Metallography in General. *Metallography* † is that branch of science which relates to the constitution and structure, and their relation to the properties, of metals and alloys. Since metallography deals with the relationship between structure of metals and their physical properties, the subject is sometimes called physical metallurgy. It should be distinguished from process metallurgy which deals with the study of extraction of metals from their ores and of refining metals and preparing them for use.

Metallography includes the study of microstructure and macrostructure of metals, space lattice arrangements of the atoms, thermal critical points, heat treatment, and examination by the X-ray beam, with particular reference to the physical properties such as tensile strength, elastic limit, ductility, hardness, toughness, resistance to fatigue, and magnetic properties.

The meanings of the terms *composition* and *constitution* should be distinguished. Composition is the term employed to indicate the proportions of the different elements of a material; constitution refers to the state or structure in which those elements or their combinations are found. For example, two metals may have the same composition but different constitutions and physical properties depending upon thermal and mechanical treatments. On the other hand, two metals may have a similar arrangement of atoms, but the properties may be different owing to differences in composition.

23. History of Development of Metallography. Sorby in 1864 in England reported the results of his studies of the microstructure of meteoric irons. In 1886 and 1887 he presented two papers, illustrated by photomicrographs of iron and steel, before the British Iron and Steel Institute. Pioneer work on the use of the microscope in studying the

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* Professor of Physical Metallurgy, Massachusetts Institute of Technology.

† Definitions of Terms Relating to Metallography, A.S.T.M. Designation: E 7-27.

structure of metals was also carried on by Martens in Germany, Osmond in France, Stead and Arnold in England, and Howe and Sauveur in the United States. By 1910 metallographic methods were in common use in industrial laboratories in the United States.

24. Use of the Microscope. While chemical analysis gives the engineer much information concerning the alloys with which he is dealing, the microscope is of great value in determining the nature of the alloy, both as to its heat treatment and as to its possible defective condition. The engineer is not usually concerned with the preparation of alloys for microscopic examination; therefore, only a brief description of the principles will be included.

A small section of the metal to be examined is polished with a series of abrasive materials, each finer than the preceding one, until a scratch-free, highly polished surface is obtained. In most cases the polished surface is treated with a chemical reagent that will attack one constituent more readily than the other and so disclose the internal structure of the alloy. This operation is called etching.

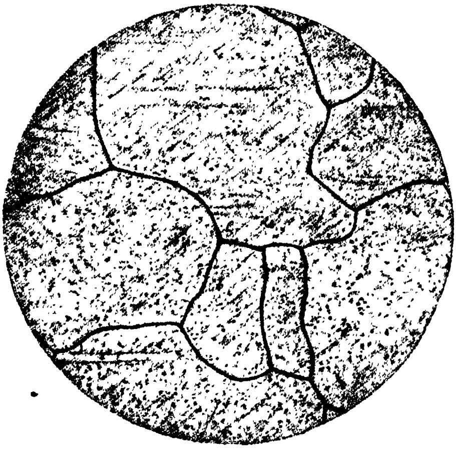

FIG. 10.—Photomicrograph of a Pure Metal (Copper) 100×. (Homerberg.)

Since metals are opaque, the microscope is provided with a device which throws a spot of light on the polished surface, and the specimen is examined by the reflected light, instead of transmitted light as is usual in the microscopic examination of transparent materials. It is often desirable to have a photographic record of the structure of an alloy. For this purpose a camera may be attached to the microscope and the magnified image transmitted to a photographic plate. An instrument especially designed for this work is known as a metallograph, and the pictures taken are photomicrographs. These are used frequently in connection with specifications and as a check on the condition of an alloy.

Photomicrographs of non-ferrous alloys are commonly taken at magnifications of 75 to 100 diameters. Magnification is the ratio of the size of the image to that of the object and is generally expressed in "diameters," thus "100×" or 100 diameters. The finer structure of steel alloys often needs a magnification of 250 diameters, and, for special work, very high magnifications up to several thousand diameters are sometimes used.

A pure metal when seen under the microscope is found to consist of a number of grains, polygonal in shape, separated by fine boundary lines (Fig. 10). The experienced observer can distinguish readily between coarse-grained and fine-grained metal.

25. The Macro-examination of Metals. Macro-examination refers to a study of materials either with the unaided eye or at a low magnification, not exceeding 10 diameters. The surface to be examined need not be so highly polished as for microscopic study but should be as smooth as convenient. The prepared surface is treated with a suitable chemical to make the structure visible. This type of treatment often discloses ingotism, carbon or phosphorus segregation, blowholes, and slag inclusion, and is of great importance as it may also indicate the direction of the *fiber* in wrought material and so give a clue as to the method of manufacture. Fig. 11 shows a macro-etch of a steel forging.

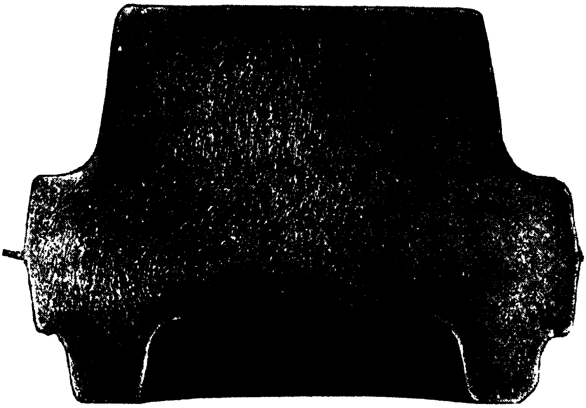

FIG. 11.—Macro-etch of Steel Forging Showing Fiber. Etched with Humphrey's Reagent. (Homerberg.)

26. Examination of Metals in Polarized Light. The examination of metals by a polarizing microscope is a special development. In polarized light the true colors of metallic oxides become visible. Applications are made in the identification of metallic compounds, phases in alloys, and coatings on metals, and in studies of grain size.

27. Crystallization of Metals. A metal is any of the metallic elements, either of very high purity or of ordinary commercial grades.* Metals generally crystallize when they pass from the liquid to the solid state. Crystallization is the arranging of the atoms of the material in a space lattice to form small solids of regular geometric outlines, such as cubes, hexagons, or tetragons.

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* Definitions of Terms Relating to Metallography, A.S.T.M. Designation: E 7-27.

Solid substances which do not have a geometric arrangement of their atoms are termed "amorphous." Asphalt is an example of an amorphous material.

Crystallization of metals usually begins simultaneously at many centers. Each crystal grows by successive additions of crystalline matter in a regular pattern, but each crystal center is differently oriented. The crystals generally develop so that they meet in irregular surfaces. Such crystals of regular space lattice but irregular form are termed *allotriomorphic* crystals. The crystals are commonly called "crystalline grains" or merely "grains." The irregular boundaries between crystalline grains are thought by some metallurgists to contain amorphous material. Allotriomorphic crystals of a pure metal are illustrated in Fig. 10.

Crystals developing under conditions which permit the forming of regular geometric exterior surfaces are termed *idiomorphic* crystals. These are rarely found.

28. Space Lattice of Crystals. Space lattice is the pattern of arrangement of atoms in a material. There are three types of space lattices of importance in metallography: cubic, hexagonal, and tetragonal. The cubic system of space lattice is by far the most common and occurs in two forms, viz., the body-centered cubic and the face-centered cubic structure. The *body-centered cubic structure* has an atom at each of the corners of a cube, shared, of course, with adjoining cubes, and an atom at the geometric center of the cube which is not shared with any other cube. (See Fig. 12*a*.) The *face-centered cubic structure* has an atom at each corner and an atom at the center of each of the six faces, making fourteen atoms in all for a single cube. (See Fig. 12*b*.)

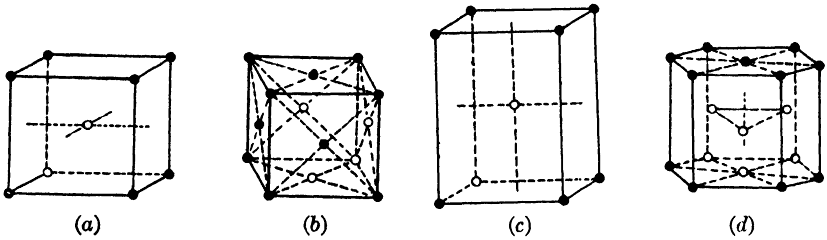
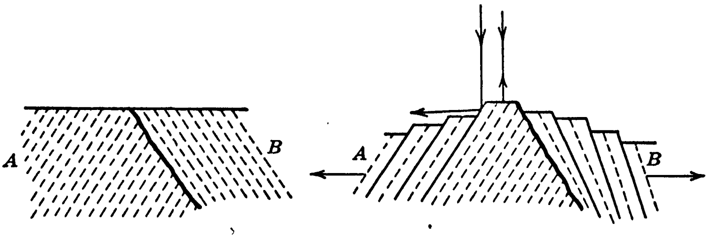

(*a*) (*b*) (*c*) (*d*)

FIG. 12.—Space Lattices of Crystals.

Alpha iron is a good example of a metal having a body-centered cubic structure. The face-centered cubic arrangement is possessed by most of the common ductile metals such as gold, silver, gamma iron, nickel, copper, and lead.

Tin has a body-centered tetragonal lattice structure which is similar to the body-centered cubic lattice but has the dimension in one axis lengthened or shortened. (See Fig. 12*c*.)

Zinc has a close-packed hexagonal structure which consists of an atom at each corner of the hexagonal lattice and at the center of the hexagonal faces and also an atom at the geometric center of each alternate triangular prism, as shown in Fig. 12*d*. Magnesium also has a hexagonal structure.



(*a*) (*b*)

Fig. 13.—Diagram Illustrating the Formation of Slip Lines: (*a*) before Straining and (*b*) after Straining.

The planes of least resistance to movement are different in the various crystal forms; this accounts to some extent for differences in physical properties.

29. Slip Lines. Many metals that have been stressed beyond their elastic limit show a number of fine black lines or bands across the polished surface when viewed under a microscope. The lines change their direction at each grain boundary but are parallel within the grains. These lines are not cracks in the surface but are steps caused by slips along the gliding planes of the crystals. Fig. 13 illustrates the formation of slip lines: in (*a*) the surface of two crystals *AB* has been polished smooth prior to straining; in (*b*) the steps in the surface have been produced by slips along gliding planes due to application of force in the direction of the arrows.

Fig. 14.—Cold-worked Cartridge Brass Showing Slip Bands 100×. (Homerberg.)

The steps appear as black bands because the light beams passing through the microscope are not reflected from these oblique surfaces back into the microscope but outside the microscope's field. Slip bands are illustrated in Fig. 14. When the amount of straining due to cold work has been extreme, the crystal grains become distorted in the direction of the force applied. Such distortions in Fig. 14 should be compared with normal metal as illustrated in Fig. 15.

30. Twinning. Slip lines should be distinguished from *twinning*. Twinning or twin crystals appear as broad bands parallel in a single grain when viewed under the microscope. (See Fig. 15.) Two parts of the crystal become symmetrical along the twinning plane owing to rotation of the parts of the crystal. Each part of the crystal becomes the mirror image of the other and hence is termed a twin. Twinning is due to straining of the metal. Mechanical twins are produced by straining; annealing twins are formed by straining followed by annealing.

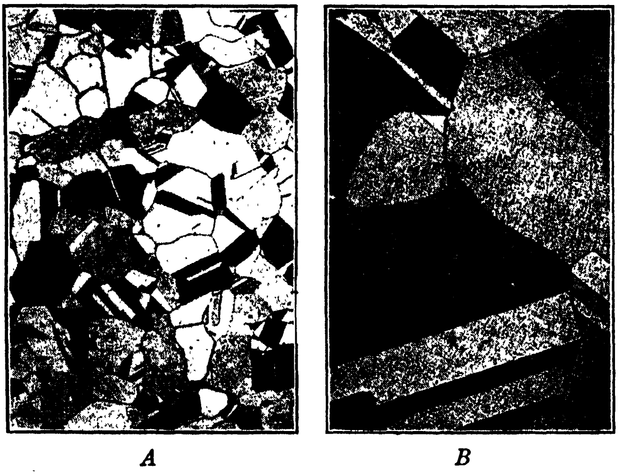


FIG. 15.—70-30 Brass Worked and Annealed 100×. (Homerberg.)
(*A*) Annealed at 650° C. (1202° F.). (*B*) Annealed at 800° C. (1472° F.).

Neumann bands are parallel lines across crystalline grains usually produced by impact or shock and are considered to be mechanical twins by most metallurgists. Since slip lines are due to steps in the surface, they may be distinguished from twinning or Neumann bands by repolishing the strained metal and again observing under the microscope to see whether the lines have been removed.

31. Cohesion and Adhesion. The strength of a crystalline structure is dependent upon cohesion between atoms in the space lattice structure within individual crystalline grains and upon adhesion between crystalline grains at the grain boundaries. Failure of ductile metals under tensile or compressive loads at ordinary temperature usually occurs by distortion of the crystalline grains and formation of slip lines within the grains. At elevated temperatures creep may occur and failure be caused by pulling apart of the crystals at the grain boundaries. This failure may occur suddenly without appreciable permanent set, indicating brittleness. These types of failures are illustrated in Fig. 95, page 251.

Elasticity of metals is due to the attraction between atoms in the space lattice. The application of a force causes a distortion in the atomic arrangement, but the attraction or bond between the atoms causes the original space lattice to be resumed when the force is removed. Modulus of elasticity, which is a measure of stiffness, may be thought of as the measure of resistance of the cohesion between the atoms against change in shape of the space lattice in crystalline grains.

32. Constitution of Metals and Alloys. An alloy is a metallic substance produced by the combination of two or more elements. For example, an alloy may consist of the combination of two metals, or of the combination of a metal with a non-metallic element.

The properties of many metals and alloys, both non-ferrous and ferrous, are determined by their behavior on cooling from the melted state and by the internal structure of the solid alloys. Some of the relationships existing between alloyed metals are fairly complex, but a knowledge of the general behavior of metals is of real service to the engineer.

The types of solids which may result from crystallization due to freezing may be classified into six groups:

1. Pure metal.
2. Chemical compound.
3. Two-layer alloy.
4. Eutectic.
5. Solid solution.
6. Eutectoid.

33. The Freezing of a Pure Metal. If a pure metal, aluminum for example, solidifies under such conditions that the changes taking place during the cooling can be studied, the following facts will be observed. The temperature will fall at a regular rate, depending on the cooling conditions, until the freezing point of the metal is reached. The temperature then stays constant until the metal has completely solidified, after which the normal cooling is resumed. These facts are shown by Fig. 16, in which the ordinates represent temperature and the abscissas time intervals.

In this figure the sloping lines indicate the cooling rate and the horizontal line represents the number of seconds taken for the metal to solidify. The length of this horizontal line depends, therefore, on the cooling conditions and the amount of metal solidifying. Other conditions being equal, the length of the horizontal line will be proportional to the amount of metal present.

34. The Chemical Compound. A chemical compound contains its elements in single definite proportions by weight, is a single definite substance, and usually has properties entirely different from those of its constituents. The cooling curves for chemical compounds are essentially the same in characteristics as those for pure metals.

35. The Two-layer Alloy. If a mixture containing 90 per cent of aluminum and 10 per cent of lead is melted, and heat effects during the cooling of the melted mass are determined as before, the curve showing the relation between temperature and time of cooling has the form shown in Fig. 17.

Here again the sloping lines indicate the cooling rate and the horizontal lines represent the intervals of time for the two heat effects which take place during the solidifying process. If several mixtures of aluminum and lead are allowed to solidify, the total weight of each mixture being the same but the proportions of the two metals varying in each, the series of curves shown in Fig. 18 will be obtained.

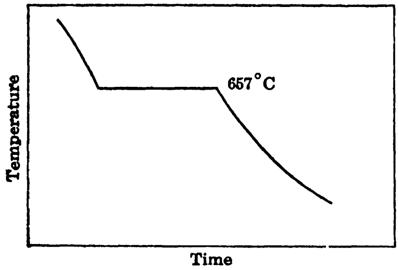


Fig. 16.—Cooling Curve for Aluminum.

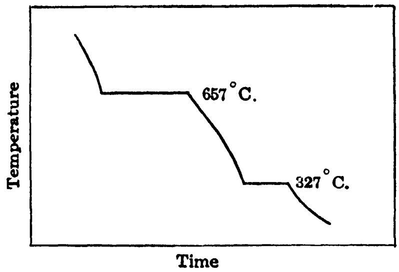


Fig. 17.—Cooling Curve for the Alloy Aluminum 90 Per Cent, Lead 10 Per Cent.

It will be noticed that in the alloys the two temperature effects are at the same temperatures regardless of the composition. The difference between the curves is that, although the total weight of metal was the same in each of the three alloys, the time at the higher temperature decreases with the proportion of aluminum, while the time at the lower temperature increases, corresponding to an increase in the proportion of lead. It is seen, further, that the temperature at the upper horizontal corresponds to the melting point of pure aluminum and that the lower horizontal break occurs at the melting point of pure lead. This means that neither metal changes the melting point of the other and suggests that the two metals do not mix. That this is the fact can be shown by melting lead and aluminum together in a glass tube. The melted mass will be found to consist of a layer of melted aluminum floating on melted lead; and, as no change takes place on cooling, the resulting mass is composed of two solid layers, one of lead, the other of aluminum.

36. The Equilibrium Diagram. It is easy to see the relation between the two metals in the simple case illustrated by the series of curves shown in Fig. 18, but it becomes difficult, if not impossible, with more complex alloy systems. Another method of showing the relationships between alloyed metals has, therefore, been developed and is shown in Fig. 19, which is known as the *equilibrium* or *alloy diagram.*

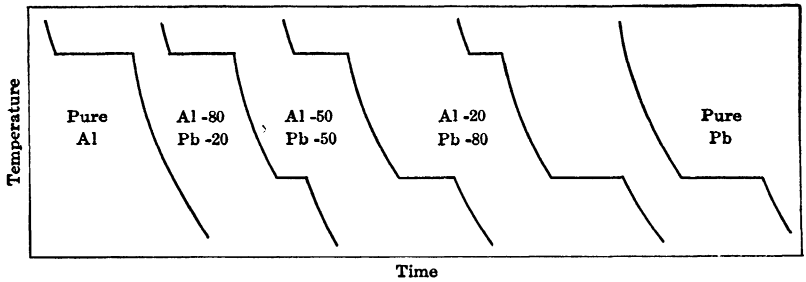


FIG. 18.—Cooling Curves for a Series of Aluminum-lead Alloys.

This diagram is made by combining the curves shown in Fig. 18, and differs from that figure in that, while the ordinates represent temperatures as before, the abscissas no longer indicate time intervals but correspond to varying percentage relations of the alloying metals. The intersection of the horizontal line at a given temperature with the vertical line corresponding to the percentage composition indicates the conditions existing at the given temperature for the alloy of given composition and may be applied equally well to any composition or any temperature. An alloy having the composition corresponding to point (*A*) on the abscissa line and at a temperature (*A*) on the ordinate line

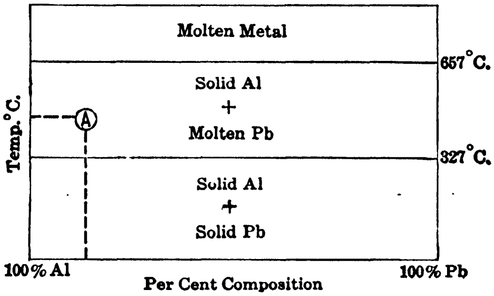


FIG. 19.—Equilibrium or Alloy Diagram for Aluminum-lead Alloys.

consists, therefore, of a mixture of solid aluminum and melted lead. The condition at any other temperature or with any other mixture may be determined from the alloy diagram in the same way. Alloy diagrams have been worked out for all the common alloys of two metals (binary alloys) and for a few alloys with three or more constituents.

The alloys of aluminum and lead, which were used to illustrate the construction of the alloy diagram, show under the microscope the two layers of aluminum and lead, respectively, each layer having the characteristic appearance of a pure metal.

The aluminum-lead alloys are of no industrial importance and were selected only because they give the simplest possible alloy diagram. A very similar industrial alloy is found in the copper-tin-lead-bronzes. Tin is dissolved in copper to make a solid solution (Art. 38) which behaves in many respects like a simple metal. Lead does not dissolve in the copper-tin alloy (bronze) but forms an emulsion with it. If the alloy is properly made, the drops of lead should be uniformly distributed through the bronze matrix. Fig. 20 shows a properly mixed alloy and a badly mixed one, as seen under the microscope. The leaded bronzes are discussed in Art. 220.

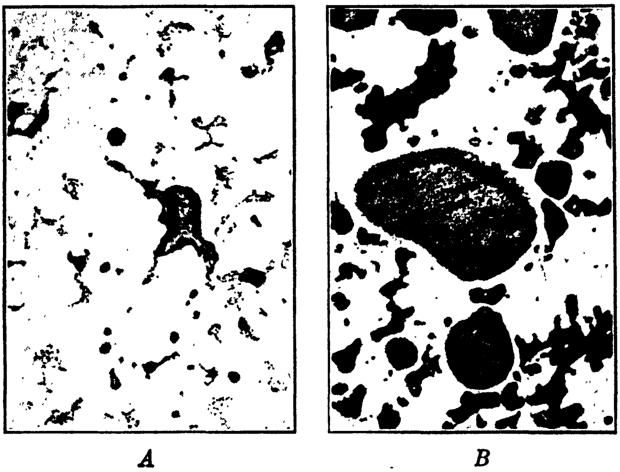


FIG. 20.—Leaded Bronze 100×. (Homerberg.)

(*A*) Good Distribution of Lead. (*B*) Poor Distribution of Lead.

37. The Eutectic Alloy. If a small amount of lead is added to tin and the changes which take place on cooling are plotted as before, a curve similar to that shown in Fig. 21 results.

If still more lead is added, the curve is similar in form but differs from that shown in Fig. 21 in that the temperature of the first break is somewhat lower than before. Conversely, if tin is added in increasing quantities to lead, the melting point of the resulting alloy becomes lower with each addition. Since the addition of tin to lead lowers the melting point of the lead and since the addition of lead to tin lowers the melting point of the tin, it follows that a certain mixture of lead and tin melts lower than any other mixture of the two metals. This alloy is called the *eutectic mixture*, or, more commonly, simply the *eutectic*. The conditions existing in a series of alloys of the eutectic type are shown in Fig. 22. This has been constructed from cooling curves of the type shown in Fig. 21.

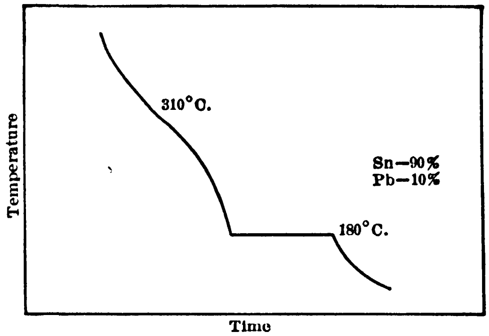


Fig. 21.—Cooling Curve for the Alloy Tin 90 Per Cent, Lead 10 Per Cent.

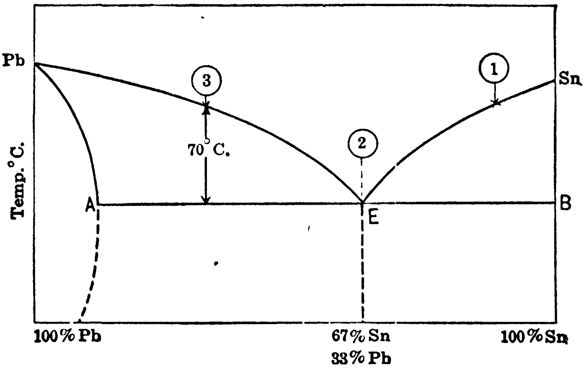


Fig. 22.—Equilibrium Diagram for the Lead-tin Alloys.

The meaning of this diagram is readily understood from a consideration of one or two definite examples. If an alloy having the composition indicated by (1) is cooled from the liquid state, no change takes place until the "liquidus" line Sn–*E* is reached. Here pure tin separates. Owing to the separation of tin, the remaining melted alloy becomes richer in lead. Tin continues to separate until the remaining melted mass has the composition *E*. Since this represents that mixture of lead and tin which has the lowest melting point (the eutectic), the alloy becomes wholly solid at this temperature (the eutectic temperature). The line *AEB* is called the "solidus." The final alloy is found by microscopic examination to consist of crystals of tin imbedded in a ground mass of eutectic mixture composed of very fine interlocked plates or needles.

An alloy of the composition (2) stays in the melted condition until the temperature *E* is reached, when it solidifies at a constant temperature. The microscope shows the granular eutectic structure which is composed of very fine interlocked plates and which is often referred to as the "thumb print" structure (Fig. 42). The eutectic is not a solution or a compound but an extremely intimate mixture of the two (or more) metals of which it is composed. There is no indication of the tin-crystals seen in alloy (1).

All alloys in the range between *E* and pure tin show but two structure elements, pure tin crystals and the eutectic. The difference between alloys in this group are differences in the relative amounts of tin and eutectic, those at the tin end consisting largely of tin with small quantities of eutectic and those near *E* composed largely of eutectic with a small number of tin crystals. *Pewter* is an alloy in this group corresponding to (1), of composition 80 per cent tin and 20 per cent lead. It is a hard metal with a silvery color that is extensively used as a decorative metal especially for household utensils. Its color may be lightened by addition of small amounts of zinc or copper.

Various solders are members of this alloy group. Of these the two most common are *tin solder,* corresponding to (2), and *plumbers' solder*, of the composition (3). The first is useful because of its low melting point, and the second, alloy (3), because it solidifies through a long temperature range (70° C.) owing to the continuous separation of solid lead along the line Pb–*E,* thus giving the plumber time to wipe joints and close up holes. The existence of the solid crystals in the melted metal makes it possible to use such an alloy in the making of a wiped joint.

The addition of a third metal to the eutectic of the two others often causes further lowering of the melting point due to the formation of ternary eutectic. These low-melting eutectics are used commercially in the manufacture of fusible plugs in automatic sprinkler systems (Art. 242).

38. The Solid Solution. The line Pb–*A* in Fig. 22 illustrates another condition in which two metals may exist after solidification from the molten state. When lead is added to tin and the melted alloy allowed to cool, the eutectic *E* always forms along the line *EB* no matter how small the amount of lead present. If, however, tin is added to lead in an amount less than about 14 per cent, a separation of the eutectic does not take place at the temperature *E* but the tin stays in solution in solid lead. This condition is known as the formation of a *solid solution,* and the resulting alloy has the appearance, under the microscope, of a pure metal, with no indication of the existence of the eutectic mixture. The two metals forming the solid solution are intimately dissolved in each other and the crystals are so nearly homogeneous that the constituent metals cannot be distinguished even under the microscope.

Alloys having less than 14 per cent of tin with lead are unsaturated solid solutions. When the amount of tin present is more than 14 per cent, the lead is no longer able to hold it in solid solution and the excess tin separates as a constituent of the eutectic. The alloy of composition (3) in Fig. 22 has a microstructure consisting of solid solution particles of tin in lead imbedded in a mass of eutectic mixture. Since lead dissolves tin to only a limited extent, the alloy is known as a partial solid solution. In other alloys the solubilities may vary with the constituent metals.

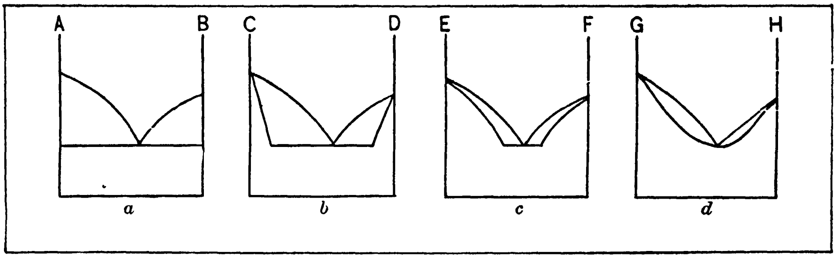


Fig. 23.—Types of Equilibrium Diagrams.
(*a*) Solid-insolubility.
(*b*) and (*c*) Partial Solid-solubility.
(*d*) Complete Solid-solubility.

39. Types of Equilibrium Diagrams. These relations are indicated by the general alloy diagrams shown in Fig. 23. The simple eutectic alloy in which neither metal dissolves in the other in the solid state is represented by (*a*). In (*b*) metal *C* dissolves to a limited extent in *D,* and *D* also dissolves somewhat in *C.* (*c*) is similar to (*b*) except that the mutual solubilities of the two metals *E* and *F* are much greater. In (*d*) the metals *G* and *H* are soluble in each other in all proportions in the solid state. This is known as complete solid-solubility. In this case metal *G* lowers the melting point of *H,* and *H* lowers that of *G.* The solution having the lowest melting point is called the *solid solution minimum* and differs radically from the eutectic in that while it is the lowest-melting alloy it is perfectly homogeneous, whereas the eutectic is as non-homogeneous as possible.

40. Alloys of Complete Solid-solubility. When two metals dissolve in each other in all proportions, each does not necessarily lower the melting point of the other. Quite commonly, one melting point is raised and the other lowered. This leads to the diagram shown in Fig. 24 and is characteristic of the alloys of copper and nickel and several other alloys of industrial importance.

Referring to Fig. 24, if an alloy *mm′* at temperature t_m is slowly cooled to the liquidus at temperature t_x, freezing begins by the separating out of crystals of composition *nn′*. Since the crystals *nn′* are richer in constituent *B* than the original melt *mm′*, the remaining liquid metal is leaner in constituent *B*. Suppose that the composition of the remaining liquid metal is *pp′*. Then, as the temperature is further lowered, the liquid *pp′* is brought to the liquidus at *s* and more crystals of composition *qq′* are formed. This process continues until the liquid metal reaches composition *rr′* and is cooled to the liquidus at temperature t_y. The solid with which this last portion of melt is in equilibrium has the composition *mm′* since the composition of the solid phase moves also to the left. The two extreme limits of composition of the solid solution are *nn′* and *rr′*, but if the rate of cooling is slow enough to maintain conditions of equilibrium constantly, diffusion takes place between the liquid and solid metal so that the composition of the crystals becomes uniformly the same as that of the original liquid metal.

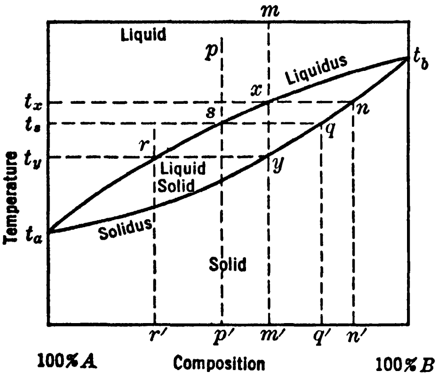


FIG. 24.—A Type of Equilibrium Diagram Indicating Complete Solid-solubility.

If the rate of cooling is not slow enough to maintain equilibrium conditions, diffusion between liquid melt and crystals will not take place, and consequently the remaining liquid will become progressively leaner in composition of *B* until crystals of pure *A* are formed at a temperature t_a. Although the crystals are formed with different compositions, diffusion between crystals tends to make the mass uniform in composition provided that sufficient time is allowed.

41. Alloys of Partial Solid-solubility. A typical equilibrium diagram illustrating mutual partial solid-solubility is shown in Fig. 25. The components of the seven characteristic areas are as follows: I, liquid solution; II, liquid solution and solid solution of *B* in *A* (called alpha solid solution); III, liquid solution and solid solution of *A* in *B* (called beta solid solution); IV, alpha solid solution; V, beta solid solution; VI, alpha solid solution and eutectic mixture of solid solutions of compositions D and F; VII, beta solid solution and eutectic mixture of solid solutions of compositions D and F.

An alloy of composition pp' will crystallize in a manner similar to that described for complete solid-solubility (Fig. 23). Under equilibrium conditions freezing will take place between temperatures z and w as the composition of the liquid solution changes from pp' to rr'. By diffusion the beta solid solution crystals tend to become uniform in composition.

The alloy mm' begins to crystallize at temperature x, the first crystals having a composition yy'. The remaining liquid metal becomes richer in B, and further lowering of temperature is required to cause additional freezing. The solid solution composition moves from yy' to D. Diffusion between liquid and solid solutions causes the solid solution crystals to attain a composition D provided that equilibrium conditions are maintained. Some liquid solution is left at this stage; it solidifies at the eutectic temperature E into a eutectic mixture composed of an alpha solid solution of composition D and a beta solid solution of composition F. It will be noted that the eutectic is not merely a mixture of A and B, but is a heterogeneous mixture of alpha and beta solid solutions. The micrograph will show a mixture of alpha solid solution crystals of composition D imbedded in a granular mass of eutectic mixture of alpha and beta solid solutions of compositions D and F respectively.

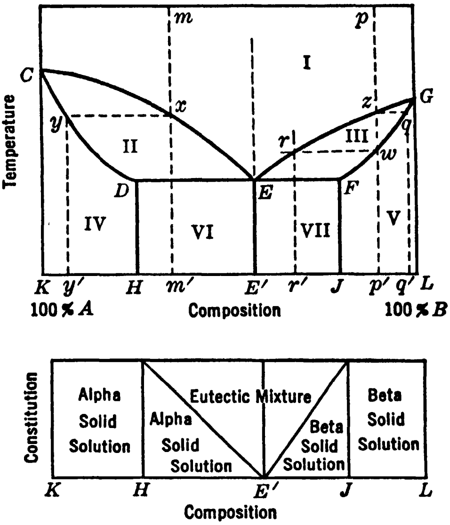


FIG. 25.—A Type of Equilibrium Diagram Indicating Partial Solid-solubility and Corresponding Constitution Diagram.

An alloy EE' of eutectic composition will solidify at temperature E forming a granular mass of alpha and beta solid solutions of compositions D and F respectively.

The constitution diagram in Fig. 25 shows graphically the constitution of the different alloys.

The solid-solution alloys, whether partial or complete, are of great importance. Most of the better-known alloys, brass, bronze, Monel metal, steel, and some others, are found in this class.

42. Formation of the Eutectoid. In considering the solid solutions it must be remembered that the general nature of such a solid solution is in most ways exactly like that of a liquid solution. On this account it is not hard to imagine that changes which take place when a liquid solution cools may also occur during the cooling of a solid solution. In Art. 37, the formation of the eutectic due to the decomposition of a liquid solution was considered. An analogous situation is often found in connection with solid solutions. An alloy which exists as a perfectly homogeneous solid solution at one temperature may decompose into its constituents at some lower temperature. Such a decomposition leads to the formation of an alloy, the structure of which is like that of the eutectic. As this structure is the result of the decomposition of a solid solution rather than of a liquid solution, it has been called a *eutectoid*. The formation of the eutectoid is shown in Fig. 26.

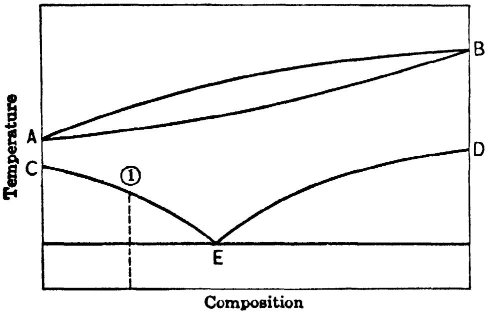


FIG. 26.—The Simple Eutectoid Diagram.

The metals *A* and *B* dissolve in each other in all proportions in the solid state and at temperatures above the line *CED*. If the cooling of alloy (1) takes place very slowly, as, for example, in cooling with the furnace in which the metals were melted, there is no difference whatever between the resulting eutectoid and the eutectic coming from a liquid melt. It has not been found possible to cool a melted alloy quickly enough to prevent the formation of the eutectic, but by rapid cooling of the alloy (1) the separation of the constituent metals may be completely or partly prevented and the alloy retained at room temperature in the solid solution condition normally existing at a much higher temperature. This operation, commercially known as "quenching," is the basis of the heat treatment of steel which is an iron-carbon solid solution decomposing with falling temperature into the eutectoid.

The four types of diagram (1) the two-layer, (2) the eutectic, (3) the solid solution, and (4) the eutectoid, or combinations of two or more of them are those found in most of the industrially important alloys. A few other types, notably those indicating compounds between the metals, are known but are of lesser importance to the engineer and will not be considered.

43. Properties of the Alloys. *Hardness.* The hardness of the eutectic alloys is practically the average of the hardness of the component metals.

The eutectic itself and alloys close to it in composition are slightly harder than would be calculated from the average values. The hardness of solid solutions is always greater than that of the constituent metals; and, when the metals are completely soluble, the hardness is greatest when the metals are present in approximately equal proportions. Compounds between metals are always extremely hard but correspondingly brittle. A metal or alloy may be hardened by being subjected to cold mechanical work, as rolling, drawing, or pressing. The cause of this kind of hardness has been widely discussed, but the various theories that have been proposed to explain it are too detailed for introduction here. A metal that has been work-hardened can be restored by annealing to its original soft condition. The brittleness accompanying mechanical hardening makes necessary the annealing to which a metal or alloy is always subjected if it is to undergo a series of operations during its fabrication.

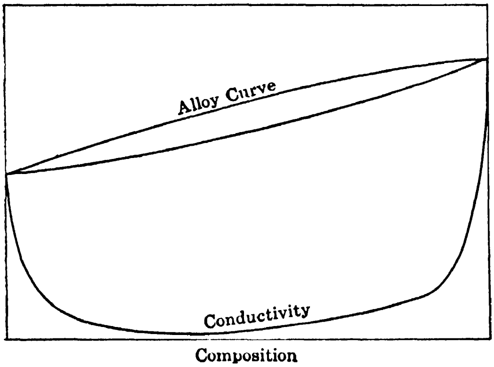


FIG. 27.—Relation between Conductivity and the Solid-solution Diagram.

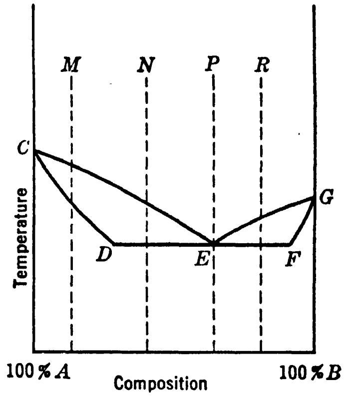


FIG. 28.—Equilibrium Diagram. (Refer to Question 13.)

Electrical Conductivity. The conductivity of an alloy is determined to a considerable extent by the relations of the alloying elements as shown in their alloy diagrams. The important general relations are as follows:

(1) In eutectic alloys the conductivity is practically the average of the conductivities of the constituent metals based on the weight percentages of the alloying elements.

(2) The formation of solid solutions causes a marked decrease in the electrical conductivity of the resulting alloys. The general effect is shown in Fig. 27.

QUESTIONS

1. Define the following terms: metallography, photomicrograph, macro-examination, allotriomorphic crystal, and space lattice.

2. Distinguish between the terms "composition" and "constitution."

3. State the type of space lattice possessed by the following metals: copper, iron, lead, nickel, tin, and zinc.

4. Discuss the significance of "slip lines."

5. What is "twinning"? What are Neumann bands?

6. Discuss the relation between strength of metals and their cohesive and adhesive properties.

7. Name six types of solids which may result from crystallization.

8. Distinguish between a mixture, a chemical compound, and a solution.

9. Distinguish between a liquid solution and a solid solution.

10. Distinguish between a eutectic and a eutectoid.

11. What is meant by complete solid-solubility?

12. What is the meaning of the term "solid solution minimum"?

13. Referring to Fig. 28, state the microscopic structure of each of the four cooled alloys whose compositions are represented by the vertical lines *M, N, P,* and *R.* Draw a constitution diagram showing graphically the constitution of these alloys. Draw cooling curves for these alloys.

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CHAPTER IV

INTRODUCTION TO FERROUS METALS

By Lloyd F. Rader

44. General. The ferrous metals comprise three general classes of material, cast iron, wrought iron, and steel. All these are produced artificially by the reduction of iron ores and subsequent treatment of the pig iron by various metallurgical processes. Cast iron, wrought iron, and steel are distinctly different materials, judged by their comparative physical properties, in spite of the fact that more than 90 per cent of metallic iron is present in each.

45. Classification of Iron and Steel. Iron products may be grouped under the following heads:

Pig iron, the product obtained by the reduction of iron ores in the blast furnace. Carbon is present in amounts not usually below 2.5 per cent or above 4.5 per cent. The iron is cast, as it flows directly from the blast furnace, into rough bars called "pigs."

Cast iron, remelted pig iron after being cast or about to be cast in final form. It does not necessarily differ from the pig in composition, and is regarded by the metallurgist as the same thing as pig iron. It is not malleable at any temperature.

Malleable cast iron, a form of cast iron which, by a special annealing treatment after casting or rolling in final form, has been rendered malleable or semi-malleable.

Wrought iron, a form of iron which is aggregated from pasty particles without subsequent fusion. Wrought iron contains slag enclosures and is initially malleable, but normally possesses so little carbon that it will not harden when rapidly cooled.

Ingot iron, a form of iron or extremely low-carbon steel that has been cast from a molten condition.

Steel, iron which has been cast from a molten mass, whose composition is such that it is malleable at least in some one range of temperature, and which may or may not harden upon sudden cooling. Steel that owes its distinctive properties chiefly to carbon is called "carbon steel." Steels of which the distinctive properties are due chiefly to the presence of elements other than carbon are called "alloy steels."

HISTORY OF DEVELOPMENT OF IRON AND STEEL MANUFACTURE

46. Early Furnaces. Little information is available regarding the early methods of manufacturing iron other than that crude furnaces were used and the finished material was made directly from the ore mixed with charcoal in one operation. The product was a small pasty mass of red-hot iron which could be hammered into shape. Natural draft and crude forms of artificial draft were used in early days.

47. Catalan Forge. A major change took place when the Catalan forge was developed by the iron workers in Catalonia, in Spain, for manufacturing wrought iron. This forge consisted of a furnace 2 feet high with a crucible about 1 foot deep to hold the heated lump of iron. The blast was derived by water power and entered the furnace through tuyères in the bottom. The increased efficiency of this furnace over previous methods was due mainly to the improved air blast. The fuel was charcoal, burned in direct contact with the metal. This type of furnace with but few improvements was used as late as the latter part of the nineteenth century to smelt ores in the United States.

48. Two-stage Process. In the fourteenth century the method of producing wrought iron direct from the ore began to be replaced by a two-stage process. The principal difficulty with single-stage operations was encountered in reducing the carbon in the iron. The charcoal fuel was an excellent carburizing agent, and every precaution had to be taken to keep the wrought iron from recarburizing to the point where it was no longer malleable and ductile. The first heating was in a shaft-type forge furnace, called a stückofen in Germany, and the second heating, carried out in a Catalan furnace, reduced the material which had been over-carburized. The wrought iron produced by this additional working was more uniform and superior in physical properties to the product of the single-stage operation.

49. Blast Furnace. During the fifteenth century the shaft-type furnace was increased in size and the draft improved so that higher temperatures were attained. The iron was heated to a point where it absorbed carbon from the fuel and thus its fusion temperature was lowered from 1500° C. to between 1130° C. and 1200° C. Since this was below the working temperature of the furnace, the product was a molten metal which was hard, brittle, and relatively weak. This marked the beginning of production of pig iron in a *blast furnace.* Pig iron is metallurgically the same as cast iron.

Coal was employed in 1619 in England in the smelting of iron ore but coke was not used in the blast furnace until 1735. Steam engines were employed for blowing air into the blast furnace during the eighteenth century. Neilson invented the hot blast in 1828 by devising a means of preheating the air blown into the blast furnace. This greatly increased the production of pig iron and reduced fuel requirements. The hot-blast stove based upon the regenerative principle was developed by Cowper in 1857.

50. Reverberatory Furnace. The development of equipment and methods of making wrought iron and steel from pig iron was a slow process. The reverberatory or air furnace was perfected and patented in 1784 by Henry Cort in England. Its principal feature was that the fuel was burned on a grate adjacent to the hearth where the iron was worked, the hot gases passing over and fusing the charge of iron, thereby removing most of the impurities by oxidation. Coke or coal could be substituted for charcoal as fuel in this furnace in producing wrought iron since the fuel was not in direct contact with the metal. The puddling process utilizing the reverberatory furnace was developed, making possible increased production of wrought iron of good quality.

51. History of Steel Making. Cementation steel was the earliest form of steel. It was manufactured by heating wrought iron in contact with charcoal so that carbon was absorbed by the iron.

Crucible steel was first produced by Huntsman in 1740. Both these steels were expensive to manufacture and were produced in small quantities. Wrought iron was more extensively used in industry than steel until 1855, when the Bessemer process was patented.

William Kelly in 1847 in Kentucky developed a process of refining pig iron in a converter by blowing air through the molten iron. This was the beginning of modern methods of making steel. Sir Henry Bessemer a few years later developed independently the same process which he patented in England in 1855. Kelly was issued a patent in the United States but he later sold the rights to his invention to Bessemer. The process is commonly called the Bessemer process. The modern process consists of blowing air through a bath of molten pig iron to remove carbon, silicon, and manganese by oxidation.

The open-hearth process was developed by the Siemens brothers in England and by the Martin brothers in France, beginning in 1856. This process is in general use today for the production of the better grades of steel. The process consists of removing impurities by oxidation in a reverberatory regenerative type of furnace.

Experiments on an electric melting furnace were carried on by Sir Wm. Siemens in 1878. Electric furnaces for smelting iron ores and refining steel were developed for industrial operation in 1898.

QUESTIONS

1. Describe the essential features of the Catalan forge.
2. Describe the history of the blast furnace.
3. Discuss the development of wrought-iron manufacture.
4. Discuss the history of steel making.

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CHAPTER V

IRON ORE AND PIG IRON

THE RAW MATERIALS OF THE IRON INDUSTRY

52. Ores of Iron. Ores of iron consist essentially of compounds of iron, usually oxides, mixed with gangue (silica, clay, etc.), and those of commercial importance contain from 25 to 70 per cent metallic iron.

Iron is extracted from ores by a process known as smelting, which consists primarily in heating of the ore to a high temperature under strongly reducing conditions in the presence of a flux. The reducing agent serves to remove the oxygen from the oxides of iron, leaving metallic iron together with such elements as carbon, silicon, manganese, phosphorus, and sulfur, which are invariably present either in the ore or in the fuel used in melting. The flux, usually limestone, combines with the gangue of the ore and the ash of the fuel, producing a fusible slag which may be separated from the metallic iron. The forms of iron ore of greatest commercial importance are as follows:

Hematite, sometimes called red hematite or red iron ore, is anhydrous ferric oxide, Fe_2O_3, containing when pure 70 per cent iron. It is the most important iron ore commercially.

Limonite, also called brown iron ore or bog iron ore, is hydrated ferric oxide, $Fe_2O_3 + [n]H_2O$, containing about 60 per cent iron.

Magnetite is the magnetic oxide of iron, Fe_3O_4, containing when pure 72.4 per cent iron. It occurs in a state of high purity in Sweden where it is extensively used.

Iron carbonate, commonly called siderite or spathic iron ore, $FeCO_3$, contains when pure 48.3 per cent iron.

The Lake Superior district is the largest iron-ore-producing region in the world, a soft red hematite of high grade being obtained in quantities sufficient to supply about 80 per cent of the tonnage used in the United States.

All ores of iron in which the phosphorus content does not exceed one-thousandth part of the iron content are classed as Bessemer ores, and all ores carrying a higher percentage of phosphorus as non-Bessemer ores. This division is due to the fact that acid Bessemer steel must contain less than 0.1 per cent phosphorus, and neither the blast-furnace reduction of the ore nor the acid Bessemer steel process is able to reduce the phosphorus content.

53. Special Preliminary Treatment of Ores. Practically all the hematite is charged into the furnace without any preliminary treatment. Some ores, however, behave more satisfactorily in the furnace after having been subjected to one or the other of the following preliminary processes.

Calcination is resorted to for the purpose of removing water from limonites or hydrous ores; removing CO_2 from carbonates; oxidizing a portion of the gangue of dense ores, particularly magnetites, thereby rendering them more accessible to the furnace gases; or rendering the ore magnetic, to facilitate subsequent magnetic concentration.

Roasting is for the purpose of removing sulfur from ores. The sulfur is present as pyrite, FeS_2, which is decomposed at a moderate heat, liberating S and forming FeS. The FeS is oxidized by air to form ferrous sulfate, $FeSO_4$, and further heating decomposes the sulfate, forming ferric oxide, Fe_2O_3, with the liberation of sulfur dioxide and oxygen.

Concentration of ores is employed occasionally for the purpose of freeing the ore of a part of the gangue, and for enriching the ore before smelting. Wet concentration is sometimes used to remove clay, loam, etc., by a simple process of washing. Another method of wet concentration is by means of jigs which separate pebbles and sand from the ore by agitation of perforated trays set in tanks of water.

Dry concentration is usually accomplished by some type of magnetic separator. If the ore is not already magnetic it is magnetized by preliminary calcination. It is then crushed and passed in a thin layer before strong magnets, the magnetic portion being thus attracted away from the non-magnetic.

54. The Flux. The function of the flux is to provide a fusible slag in which the non-metallic portion of the ore may be carried off. The exact character and amount of the flux needed will depend upon the composition of the ore and fuel, and the characteristics of pig iron required. In general, it may be said that a basic flux is required for acid gangues (high in silica, alumina, etc.), while an acid flux may be required where the gangue is basic (high in lime, magnesia, or alkaline matter). As a rule, gangues are acid in character and therefore the fluxes are usually basic in character.

The most common form of basic flux is limestone, which should be very pure. Pure or high-calcium limestones are not always available and magnesian or dolomitic limestones are sometimes used. The replacement of a considerable part of the calcium by magnesium does not appear to impair the efficiency of the flux appreciably.

The flux serves another purpose, besides taking care of the gangue and ash. The sulfur in the charge, whether in the ore or in the fuel, combines with the lime of the flux, forming calcic sulfide, which is removed in the slag.

55. The Fuel. The fuel for a blast furnace must serve as a reducing agent as well as a source of heat. The fuel required from the standpoint of heat always exceeds the amount required for reduction, and therefore only the thermal value of the fuel need be considered in this connection.

The rapidity of melting attained in the furnace is dependent upon the rapidity of heat production, which, in turn, is dependent upon the rapidity of oxidation of the carbon of the fuel by the oxygen of the air. It is therefore desirable that a fuel, in addition to having a high calorific value, have a porous rather than a dense structure, thereby exposing additional surface to the action of the oxygen. It is further necessary that it possess sufficient firmness while being heated so that it will not fill up the interstices of the charge, thereby impeding the flow of the gases.

All solid fuels consist of a combustible portion, carbon and hydrocarbons, which combine with oxygen to form gases, and an incombustible portion which remains as a solid residue called ash, and must be fluxed from the furnace.

Three classes of solid fuel have been used in the blast furnace: coal, coke, and charcoal. From the standpoint of structure and accessibility to oxidation, charcoal surpasses coke and coke surpasses coal. From the standpoint of firmness, coke stands first and charcoal is least desirable. Most of the hard, well-made cokes withstand the pressure of the charge very well. Bituminous coals melt down during heating, and anthracites under similar circumstances are likely to splinter into fine particles.

Charcoal is the purest of the solid fuels and has the least ash, but it is expensive. Anthracite coal is less pure than charcoal and has much more ash; it is, however, much purer than coke and has very much less ash. Difficulty is sometimes experienced with coke on account of its sulfur content. Each type of fuel has its advantages and all are used, but coke is most commonly employed.

MANUFACTURE OF PIG IRON

56. The Blast-furnace Process in General. Practically all the iron used commercially, whether as cast iron, wrought iron, or steel, is first reduced from the ores in a blast furnace to form pig iron. Considerable research work is being carried on with the object of devising a process for the production of steel directly from the ore, but nothing of commercial value has been developed. The process of smelting iron in the blast furnace consists essentially of charging a mixture of fuel, ore, and flux into the top of the furnace, and simultaneously blowing in a current of air at the bottom. The air burns the fuel, forming heat for the chemical reactions and for melting the products; the gases formed by this combustion remove the oxygen from the ore, thereby reducing it to metallic form; and the flux renders the earthy materials fluid. The gaseous products of the operation pass out at the top of the furnace; the liquid products, pig iron and slag, are tapped off at the bottom. The escaping gases are combustible, and therefore are conducted through pipes to boilers and stoves,

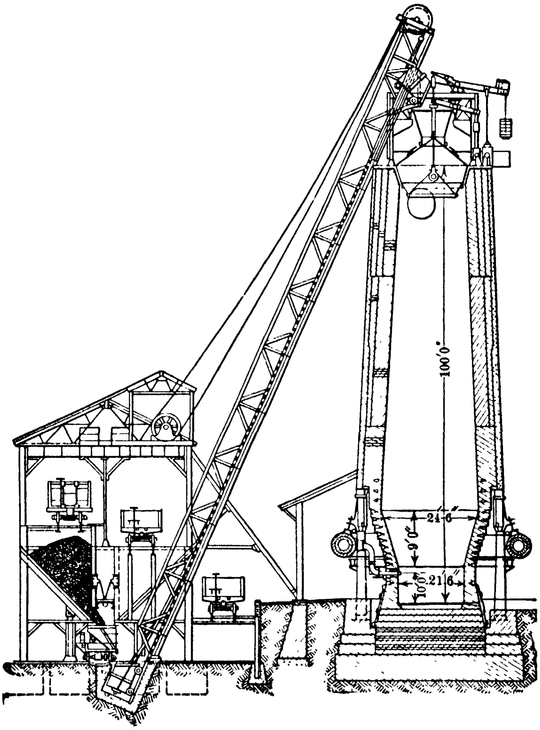

Fig. 29.—Blast Furnace and Charging Mechanism. (Campbell.)

where they perform the useful service of heating the blast and raising steam or operating internal-combustion engines.

The essential equipment of a smeltery consists of the blast furnace itself, the equipment for handling the charges and the products, stoves which preheat the air used for the blast, and blowing engines which supply air under pressure and deliver it to the furnace.

57. The Blast Furnace and Its Mechanical Equipment. The blast furnace, Fig. 29, consists of a vertical shaft built of steel and lined with firebrick. The lower portion, called the hearth or crucible, is cylindrical, about 10 feet high, and 21 to 22 feet in diameter. It contains the tuyères, the cinder notch, and the iron notch, and serves as a crucible in which the molten products of the operation are collected. Above the hearth the walls diverge, forming an inverted truncated cone called the bosh, which is 8 to 12 feet high and 24 to 25 feet in diameter at the widest point. Above the bosh extends the stack, converging to a diameter of about 17 to 18 feet at the throat at a height of 45 to 60 feet above the bosh.

The top of the stack is equipped with two cone-shaped bells and two hoppers for charging the materials without losing hot gases from the furnace. The materials are dumped into the upper hopper and the upper bell is lowered, causing them to fall into the lower hopper. The upper bell is closed and the lower bell opened, permitting the materials to flow into the stack.

An inclined track or skipway is used to haul the buckets or skips of materials from the ground to the top of the furnace. The engines are located and operated on the ground.

The ring of tuyères through which the hot blast of air is driven pierces the hearth lining just below the bosh. Both the tuyères and the tuyère blocks are protected from burning by being of hollow metal construction and cooled by water circulating through them. Air is forced through the tuyères under a pressure of approximately 15 pounds per square inch.

The bustle pipe is an annular steel pipe lined with firebrick, encircling the bosh, which conducts the hot blast from the hot-blast main to the tuyères.

The hole for tapping off the liquid slag, called the cinder notch, is located on the side of the hearth about 3 feet below the tuyères. This also is protected by a water-cooled casting. It is closed by stopping up the hole by an iron bar having an enlarged end, until the slag itself has solidified and plugged the hole.

The iron notch is at the front of the furnace and about 2 feet above the furnace bottom. It consists of an opening in the brickwork several inches square which is closed by means of a semi-plastic clay that burns solidly into place. The clay is drilled out when it is desired to tap the furnace. The opening is closed by means of a steam or air reciprocating clay gun or an electric rotary clay gun; with the rotary gun the clay is forced in continuously under a high pressure against the full blast pressure of the furnace, thus permitting continuous operation of the furnace.

Each furnace is equipped with three to five hot-blast stoves. A stove consists of a vertical steel cylinder, 20 to 22 feet in diameter and 80 to 110 feet high, containing two firebrick chambers. The central chamber is open; the outer annular chamber is divided into a large number of small flues. Gas from the blast furnace and a definite proportion of air are admitted at the bottom of the open chamber and burned. The products of combustion rise to the top of the furnace and pass downward through the small flues and thence to the stack. The greater part of their heat is taken up by the brickwork of the flues. After gas has been burned in a stove for about three hours, the stove is hot enough to heat the blast.

Air from the blowing engines is now admitted at the bottom of the small flues in the outer chamber and passes upward, taking up the heat stored in the brickwork and attaining a temperature of about 538° C. (1000° F.). Thence it passes downward through the central flue to the hot-blast main leading to the furnace.

58. The Operation of the Blast Furnace. The blast furnace has five distinct duties to perform:

Deoxidation of the iron ore.
Carburization of the iron.
Melting the iron.
Conversion of the gangue to fusible slag.
Separation of the molten iron and the slag.

Deoxidation of the Iron Ore. The recovery of iron would be impossible without deoxidation, because of the operation of the general principle that oxidized bodies in a state of fusion will not unite with unoxidized ones. The application of this principle to the metallurgical processes in iron and steel making may be stated as follows:

First, when an element such as carbon, silicon, or phosphorus, existing in chemical union with a metal, combines chemically with oxygen, the resulting oxidized product must, when melted, separate itself from the remaining metallic portion.

Second, if oxidized metal parts with its oxygen and becomes reduced to the metallic state, the newly liberated portion joins the metal in the furnace.

If, therefore, the iron were not reduced, the iron oxide would not be recovered, but would be lost with the slag.

Carburization of the Iron. Carburization of the iron is essential because at the temperature attained in at least the greater part of the melting zone it would be impossible to melt free iron, whereas iron saturated with carbon is sufficiently superheated beyond its melting point to make it very fluid, so that it easily becomes separated from the slag in the hearth.

Melting the Iron. When fusion takes place all oxidized bodies unite to form the slag and expel therefrom all fused unoxidized bodies. It is, therefore, essential that the iron be fused in order that it may be expelled from the slag. The molten iron will necessarily absorb all deoxidized substances such as silicon, manganese, and phosphorus, which exist as free metals or metalloids in the lower portion of the furnace. Carbon will also be absorbed until the saturation point is reached.

It is further essential that the iron be not only fused but also superheated, in order that it may remain fluid until drained from the furnace and cast into pigs or transported to steel furnaces.

Conversion of Gangue to Fusible Slag. The function of the slag formed in the blast furnace is primarily the elimination of all nonvolatile matter, in the gangue of the ore and in the fuel, that does not properly belong in pig iron. This can be accomplished only by giving to the slag such a composition that it will offer a greater attraction to the impurities than the metal offers.

The slag-making materials consist of the gangue of the ore, the ash of the fuel, and the lime of the flux. The chemical nature of the slag and consequent metallurgical action are controlled by varying the relation of lime to the other slag-making constituents in the furnace charge. The slag-making materials upon fusion form a molten silicate of lime, together with magnesia and alumina. The alumina and earthy and alkaline bases naturally enter into the slag, since they exist as oxides and are not reduced in the furnace. In addition, the bulk of the silicon will enter the slag as silica (SiO_2), and most of the sulfur, by an entirely chemical action, enters the slag as sulfide of calcium, which, although an unoxidized body, does not unite with the molten iron, but appears to dissolve in the slag.

Separation of Iron and Slag. The two substances are chemically mutually repellent, and both are very fluid and of different specific gravities. The slag floats upon the molten iron in the hearth of the furnace and may be readily tapped off through the cinder notch above the level of the iron.

Burdening. The proportion of ore and flux to the fuel in the furnace charge is called the furnace burden. Successful operation depends more upon the proper burdening than upon any other single factor in the furnace management. The method of determining the furnace burden is somewhat complex, and is dependent in its details upon the experience gained in the use of given ores.

The materials are loaded from stock piles into transfer cars of bottom-dumping type and dumped into bins. Coke is charged by volume directly into the skip car. Iron ore and limestone are dumped from the bins into transfer cars, equipped with weighing devices and called weighing lorries, which move between the bins and skip car. The materials are placed alternately in the skip car in proper proportions and then carried up the inclined skipway to the top of the furnace where they are charged into the blast furnace by means of the double bell and hopper. Various devices are used for distributing the stock evenly as it falls into the furnace, the intention being the prevention of segregation of the coarse and fine material.

Capacity. Blast furnaces are built in sizes for a daily capacity of 100 to 1000 tons of iron. The blast furnace of the dimensions shown in Fig. 29 would have a capacity of about 800 tons of pig iron per 24-hour day. Such a furnace would require about 2700 tons of charge material per day consisting of ore 1500 tons, coke 800 tons, and limestone 400 tons. Approximately 3000 tons of air would be required and about 6,000,000 gallons of water per 24 hours. About 300 tons of slag would be produced.

Control. The hot-blast stoves are controlled by a series of valves, which regulate the admission of gas, the admission of air from the blowing engines, the outlet of hot gases to the furnace, and the chimney draught while "on air."

The hotter the furnace the more powerful will be the deoxidizing action. Increasing the fuel ratio has a direct effect upon furnace temperature and an indirect effect in increasing the deoxidizing action. Increasing the lime-magnesia content of the slag has the effect of raising its melting point, and as a result the hearth temperature is again increased with consequent increase in the strength of deoxidizing agencies.

Tapping. The slag must be tapped off within ten to fifteen hours after starting the blast and thereafter about every two hours, the intervals becoming shorter as the level of the molten iron rises toward the level of the slag notch. The iron is tapped about 20 to 30 hours after starting the blast and thereafter at intervals of about 4 to 5 hours. Peep holes are provided in the furnace walls so that the proper time for tapping slag or iron may be observed.

Handling the Products. The iron when tapped from the furnace is handled in one of two general ways: by casting into pigs, or, still molten, in ladles.

Formerly all the iron was cast in sand pig-beds, which consist of a series of parallel depressions molded in a bed of silica sand on the floor of the cast-house. Fig. 30 shows such a pig-bed. The individual depressions are connected to cross runners which in turn connect with the main runner leading from the tap hole. Sand casting is now seldom practiced.

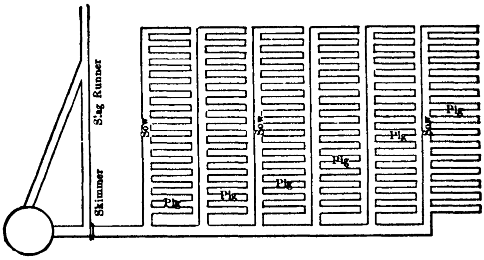

Fig. 30.—Sand Casting Pig-bed.

A modification of the sand pig-bed, the chill pig-bed, is sometimes used. It is a pig-bed made of cast iron, molded in shape very similar to that of the sand pig-bed, but not requiring any preparation beyond sprinkling with a clay wash to prevent the pig iron from sticking to the molds.

The iron pigs are broken from the cross runners by hand sledges and bars or by a mechanical pig breaker, and the cross runners are similarly broken up into convenient lengths.

One type of pig-molding machine is illustrated in Fig. 31. The machine consists essentially of a continuous series of pressed steel molds carried on an endless chain. The iron runner of the furnace delivers the molten iron into a ladle which is discharged into a spout, whence the metal is poured into the molds as they slowly travel past. The iron quickly chills and is discharged into a car when the mold passes over a sheave at the end of the run. On the return the molds are immersed or sprayed with limewater to prevent the pigs' adhering. The cooling of the pigs is usually facilitated by depressing the chains and running them through a tank of water.

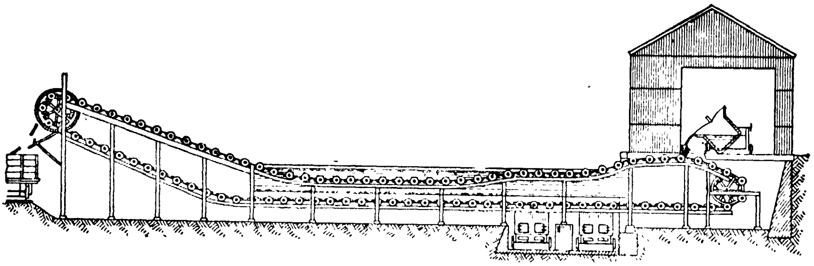

FIG. 31.—Pig-molding Machine.

The blast furnace is so often operated in direct conjunction with a steel plant that the iron is very commonly not cast into pigs at all, but is run directly into ladles which transport it to the steel furnaces. The ladle is built of steel, mounted on trunnions on a car-truck, and lined with firebrick. Its capacity is usually 20 tons or more.

The slag which accumulates above the level of the cinder notch is tapped off at intervals of about two hours, while the iron notch is closed. When the iron notch is opened, iron free from slag flows at first, but later on in the cast a quantity of slag accompanies the iron, floating on top just as it does in the hearth. This slag is easily separated from the iron by a skimmer placed in the main iron runner. The skimmer usually consists of a permanent cast-iron trough, having a depression followed by a dam over which the iron must flow. The skimmer is suspended over the depression at such a height that it rests on top of the stream of iron and effectually prevents the slag from being carried over the dam. An opening in the side of the trough allows the slag to overflow into a runner, whereby it is carried to the main slag runner which leads from the cinder notch to the point where the slag is discharged into ladles and carried to the slag dump.

59. The Electric Reduction of Iron Ores. The electric furnace is used to a limited extent in the production of pig iron. In the blast furnace, fuel must be supplied to serve two purposes: the introduction of carbon, the oxidation of which supplies the necessary heat; and the introduction of carbon to act as a reducing agent. In the electric furnace, the requisite heat is supplied by electrical means and the only carbon required is that needed for strictly reducing purposes. It has been shown that the electric furnace needs about one-third the amount of carbon required by the blast furnace.

On the other hand, the cost of heat produced by electrical means will usually exceed the cost of heat produced by the combustion of fuel, except in ore districts where the price of fuel is very high and that of electric power low. It is only in such districts, therefore, that the commercial extraction of iron by electric means can be successful.

60. Classification of Pig Irons. Pig irons are classified according to method of manufacture, the purpose for which they are intended, and composition.

Method of manufacture.

Coke pig: smelted with coke and hot blast.
Charcoal pig: smelted with charcoal, with either hot or cold blast.
Anthracite pig: smelted with anthracite coal and coke, with hot blast.

Purpose for which intended.

Bessemer pig: for Bessemer or acid open-hearth process.
Basic pig: for basic open-hearth process.
Malleable pig: for malleable cast iron.
Foundry pig: for cast iron.
Forge pig: an inferior foundry pig used for manufacture of wrought iron.

Chemical composition.

Silicon pig: high in silicon.
Low-phosphorus pig.
Special low-phosphorus pig.
Special cast irons (spiegeleisen, ferromanganese, ferrochrome, etc.).

The second of these classifications is most commonly used.

The composition of the different grades is usually specified within the following limits:

	Silicon, per cent	Sulfur, per cent	Phosphorus, per cent
Bessemer pig	1–2.00	not over 0.05	not over 0.10
Basic pig	under 1.00	under 0.05	not specified
Malleable pig	0.75–2.00	not over 0.05	not over 0.20
Foundry pig	1.50–3.00	not over 0.05	0.50–1.00
Forge pig	under 1.50	under 0.10	under 1.00

Any of the above irons may be called "sand-cast pig," "chill-cast pig," or "machine-cast pig" according to the method of molding.

Pig iron as such has no structural uses, but a considerable amount is used after remelting, in the shape of cast iron. By far the greater part of all of the pig iron made is converted into steel either by the Bessemer process or the open-hearth process, or into wrought iron.

QUESTIONS

1. Name the common iron ores, and state their chemical formulas.

2. Discuss briefly the characteristics of ore obtained from the principal iron-ore region in the United States.

3. What is a flux? What materials are used as flux in reducing iron ore?

4. Sketch a blast furnace, naming the principal parts and showing approximate dimensions.

5. Describe how hot-blast stoves are used in connection with the blast furnace.

6. What is the "regenerative principle"?

7. What would be the charge for a blast furnace of a daily capacity of 800 tons of pig iron?

8. In blast-furnace operation why is it necessary to carburize the iron?

9. Classify varieties of pig iron according to the purpose for which they are intended.

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CHAPTER VI

STEEL

61. Definition. It is not possible to make a strict definition of steel which is concise and at the same time not in conflict with current usage. In the early days of the iron industry it was easy to distinguish between steel and cast iron by declaring any form of iron which was malleable to be either steel or wrought iron—steel if it would harden upon sudden cooling, otherwise wrought iron. These distinctions will not hold at the present time, however, since many grades of alloy steel are now made which will not harden upon sudden cooling; some steels are not malleable except through a certain range of very high temperatures; and one grade of iron, malleable cast iron, is malleable (after annealing) but cannot be classed as steel.

Professor H. M. Howe has proposed the following definition, which, although cumbersome, covers the ground adequately: "Steel is that form of iron which is malleable at least in some one range of temperature, and in addition either (*a*) is cast into an initially malleable mass; or (*b*) is capable of hardening greatly by sudden cooling; or (*c*) is both so cast and so capable of hardening."

The provision in the definition that steel "is malleable at least in some one range of temperature" distinguishes steel from cast iron and pig iron without excluding certain special steels like chrome and manganese steel, which are malleable only through a short range of high temperatures; the provision that it is "cast into an initially malleable mass" excludes malleable cast iron, which is rendered malleable by special treatment after being cast or rolled; and either the provision that it is "cast," or the provision that it "is capable of hardening greatly by sudden cooling" serves to differentiate it from wrought iron (which is never cast and is never capable of hardening), without excluding cementation or blister steel, which is not cast but will harden.

Professor Albert Sauveur gives the following definition: "Steel is a malleable alloy of iron and carbon, usually containing substantial quantities of manganese."

62. Classifications of Steel. Steels are classified according to method of manufacture as:

Blister or *cementation steel, crucible steel, Bessemer steel, open-hearth steel, duplex steel,* and *electric steel.*

Steels are further roughly classified according to carbon content as:

Soft, mild, or *low-carbon steel,* containing from 0.05 to 0.15 per cent carbon.

Medium or *medium-carbon steel,* containing 0.15 to 0.30 per cent carbon.

Half-hard or *medium-high-carbon steel,* containing from 0.30 to 0.60 per cent carbon.

Hard or *high-carbon steel* containing from 0.60 to about 1.50 per cent carbon.

Steels are also classified according to the uses for which their properties fit them, such as:

Rivet steel, structural steel, machinery steel, rail steel, spring steel, tool steel.

THE MANUFACTURE OF STEEL

63. Steel-making Processes. Two methods of steel making by the carburization of wrought iron have been developed: the *cementation process,* which produces blister or cementation steel by the carburization of wrought iron without fusion; and the *crucible process,* which produces crucible steel by the carburization of wrought iron in a fused condition.

The two principal methods of steel making by the refining of pig iron (with or without the admixture of iron and steel scrap) are the *Bessemer process,* which produces Bessemer steel by blowing finely divided air currents through molten pig iron contained in a retort-shaped furnace called a "converter," the impurities being oxidized and thus removed in the slag, carbon being subsequently added; and the *open-hearth process,* which produces open-hearth steel by subjecting pig iron and scrap to the oxidizing flame of gas and air burned in a reverberatory regenerative furnace, carbon being restored after the removal of the oxides in the slag.

Other processes of making steel from pig iron or pig iron and scrap are usually combinations of the Bessemer process and the open-hearth or of electric-furnace methods with either the Bessemer or the open-hearth process, and are known as duplex processes.

In addition to its employment in the above processes, the electric furnace is used in the direct melting and refining of electric steel.

64. The Cementation Process. The principle which underlies the operation of steel making by the cementation process is that iron at a bright red heat will absorb carbon by an action which appears to be a traveling of solid carbon into solid iron, thereby forming a solid solution of iron and iron carbide.

The bars of wrought iron which are used for the cementation process are generally very pure iron made by the charcoal-hearth process. They are about 3 inches wide, 5/8 inch thick, and of a length corresponding to the length of the cementation pots.

The pots are filled with alternate layers of iron bars and charcoal, and the tops are luted tight with a material which at first permits the escape of gases but later becomes gas-tight.

The required temperature (about 700° C. [1292° F.]) having been attained, the carbon begins to soak into the iron at a rate of about 3/8 inch per 24 hours. The time required for the completion of the process depends upon the grade of steel produced. Mild heats require the maintaining of the maximum temperature for a period of 7 to 8 days; medium heats, about 9½ days; and high-carbon heats, about 11 days. Since the carburization proceeds from the exterior of the bars inward, the carbon content decreases progressively toward the center, and an unaltered core will be found in very mild bars.

The presence of some slag in the original wrought-iron bars is responsible for the appearance of blisters on the surface of the bars, which have been formed by the evolution of carbon monoxide gas when the carbon combined with the ferrous oxide of the slag. The presence of these blisters accounts for the term "blister steel," which is often applied to steel made by the cementation process. Very little steel has ever been produced by this process in America.

65. The Crucible Process. The crucible process consists essentially in the melting of wrought iron in closed crucibles of refractory material, the carburizer being placed in the crucible with the iron, together with any special alloying element desired. The details of the process vary with the type of furnace.

The crucibles are usually charged outside the furnace. The larger pieces of iron are first inserted, next the charcoal and ferromanganese or oxide of manganese, and lastly the smaller pieces of iron. The weight of the charge varies from 50 to 100 pounds.

The iron of the crucible charge should be pure puddled iron, but wrought-iron scrap and even soft-steel scrap is often substituted for a considerable part of the charge. Blister steel made by the cementation process is very often used in place of wrought iron in English practice.

The carburizing agent is charcoal, which is added in small lumps. Ferromanganese or oxide of manganese is added to aid in forming a liquid slag and to add a little manganese to the metal. Special elements, such as chromium, tungsten, manganese, or vanadium, are added when special steels of the class called "alloy steels" are to be produced.

The crucibles having been charged, the covers are put on and the temperature is gradually brought to a melting heat. The process is thereafter divided into two stages called "melting" and "killing." The melting requires from two to four hours, depending largely upon the composition of the charge. Low-carbon heats take much longer than high-carbon, since low-carbon stock melts at a much higher temperature. Killing or dead melting consists in holding the steel at a melting temperature until it does not evolve gases, and will pour dead, and produce sound ingots.

When the operation of killing is complete the crucibles are lifted out of the melting-hole and the covers are removed. The slag floating on top of the steel is skimmed off, and the steel is poured into cast-iron ingot molds having a cross-section 3 to 4 inches square.

Very wide ranges in composition and properties of crucible steels are obtainable. The composition is sometimes uncertain owing to the variable amount of carbon and silicon that may be absorbed from the crucible walls. Ingots are therefore always graded by breaking off the worthless upper portion containing the pipe and examining the fracture. Chemical analysis is usually employed to supplement examination of the fracture, and the ingots are separated into several grades of similar analysis.

No sharp subdivision of grades and uses of crucible steel can be made, but Table I shows in a general way the type of steel required for different classes of tools:

TABLE I

Grading of Carbon Crucible Steels

Uses	Carbon, per cent	Manganese, per cent	Silicon, per cent	Sulfur, per cent	Phosphorus, per cent
Battering tools..... Hot-work tools.... Dull-edge tools, etc.	0.45–0.65	0.20–0.50	0.20–0.30	0.02–0.060	0.015–0.050
Dies, axes, large drills, reamers, etc.	0.65–0.85	0.20–0.40	0.20–0.30	0.015–0.030	0.012–0.025
Chisels, knives..... Drills, lathe tools...	0.85–1.10	0.15–0.30	0.15–0.25	0.010–0.020	0.010–0.020
Razors, fine lathe tools and drills.... Gravers' tools, etc..	1.10–1.50	0.10–0.25	0.12–0.25	0.005–0.015	0.005–0.015

66. Acid and Basic Steel Processes. Both the acid and basic processes are employed in connection with the Bessemer converter process and the open-hearth furnace process. In the acid process the slag is of acid character, that is, has a high silica content, while the slag in the basic process is made basic by the addition of lime or limestone as a flux.

The refractory lining of an acid furnace is made of acid material such as silica or ganister in order to prevent scouring, since any unsatisfied silica in the slag would tend to reach saturation by attacking any bases in the lining with which it might come into contact at high temperature.

Silicon, manganese, and carbon may be removed by means of the acid process, but phosphorus and sulfur cannot be eliminated from the steel. Phosphorus is an especially undesirable ingredient in steel because it greatly reduces shock resistance. Low-phosphorus pig iron must be used in the acid process to produce good-quality steel.

The furnace in the basic process must have its lining composed of basic refractories such as magnesite or dolomite, since any excess base in the slag would tend to neutralize itself by scouring an acid lining.

The basic process can be so conducted as to accomplish the removal of phosphorus and sulfur as well as silicon, manganese, and carbon. Therefore, pig iron produced from low-grade ores may be utilized. In general, it is possible in the basic process to utilize materials for the charge that vary considerably in chemical composition.

THE BESSEMER PROCESS

67. General. The Bessemer process consists of the removal of most of the impurities in pig iron, by oxidation, through the agency of finely divided air currents blown through a bath of molten iron contained in a vessel known as a converter. The addition of a recarburizer after blowing is generally necessary to give the blown metal the required carbon content. The process may be either acid or basic, depending on the nature of the slag formed.

68. Acid Bessemer Process. The following operations constitute the essential features of the acid Bessemer process, commonly called the American Bessemer process:

Molten pig iron is brought from the blast furnace in hot-metal ladles and discharged into a large reservoir called the mixer.

The mixer supplies molten iron as required to charging ladles, which in turn discharge into the converters, the latter being rotated into a horizontal position during charging.

The air blast of the converter is started, and the vessel is elevated into a vertical position. The finely divided air currents pass up through the molten metal for a period of about ten minutes, by which time the impurities will have been practically eliminated by oxidation.

The converter is again turned into a horizontal position, the wind is cut off, and the recarburizer is added in order to obtain a steel of any desired carbon content.

The molten steel is poured from the converter into a ladle which is swung by a crane over a series of cast-iron ingot molds into which the metal is teemed.

When the ingots have cooled sufficiently, the molds are stripped off and the ingots are placed in soaking pits or reheating furnaces, where they remain until their still molten interiors have solidified and the temperature of the metal has become equalized throughout.

The hot ingots are transferred to the rolling mills where, by a series of rolls, they are reduced first to blooms and then to any desired shape for use in construction. Presses sometimes replace rolls.

The Pig Iron Used. Since it is impossible to remove either phosphorus or sulfur from the iron in the acid process, a grade of pig iron specially low in these elements is required. The usual limits of composition of "Bessemer pig iron" are:

Silicon, per cent	Manganese, per cent	Carbon, per cent	Phosphorus, per cent	Sulfur, per cent
1.0–2.0	0.4–0.8	3.5–4.0	0.07–0.10	0.02–0.07

At least 1.0 per cent of silicon is required in order to insure the production of a sufficient quantity of satisfactory slag, and also to provide heat. The oxidation of the silicon is the principal source of heat in the converter, the amount so derived being much greater than that derived from the oxidation of the carbon and the manganese.

69. The Bessemer Converter. The Bessemer converter consists of a heavy steel pear-shaped shell supported upon two trunnions upon which it can be rotated. The upper portion of the shell may be either concentric or eccentric. A section of a concentric converter showing a hollow trunnion connected by a pipe and slip ring with the windbox in the bottom is shown in Fig. 32. The bottom of the converter is pierced with a large number of small holes, called tuyères, through which the air blast is forced by means of a blower from the windbox up through the molten metal.

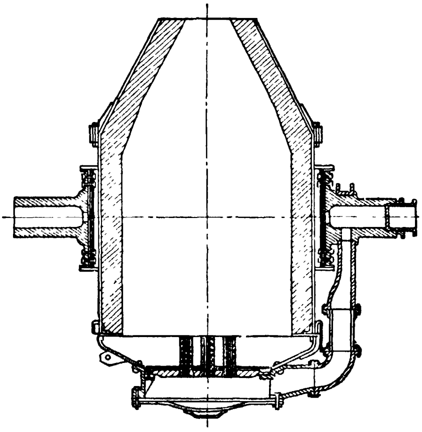


FIG. 32.—12- to 15-ton Bessemer Converter. Concentric Type.

The clear opening at the converter mouth is usually from 2 feet to 2½ feet in diameter, the inside diameter of the cylindrical portion is about 8 feet, and the height from inside of bottom to "mouth" is about 15 feet. These dimensions apply to the average-sized converter, having a capacity of 15 tons. Converters, however, have capacities all the way from 1 ton to 25 tons.

The lining of the converter is usually from 12 to 15 inches thick, and is made of very refractory material of strongly acid character, silica being the principal constituent. In American practice, ganister blocks or bricks laid with thin fireclay joints are usually employed. The lining is repaired between heats with a mixture of siliceous material and clay, and more extensive repairs are made during shutdowns. Under average conditions a lining may be made to last for several months—perhaps 10,000 to 12,000 heats—before it need be entirely replaced. A new lining must be dried, and a cold lining must be heated to a red heat before the converter is charged.

The lining of the bottom which is 24 to 30 inches thick is made up of damp siliceous material bound together with clay in which the molded tuyère brick are set. Each tuyère brick is about 30 inches long and has about 10 blast holes each approximately ¼ inch in diameter. On account of the fact that uncombined iron oxide has a strongly corrosive action on the lining, the bottom is corroded very rapidly, especially in the vicinity of the tuyères, where the air encounters the molten iron. This limits the life of the bottom lining to about 20 or 25 heats, even though repairs are made between heats.

On this account the bottom of the converter is made easily detachable, the fastenings to the body being links secured by keys which can be quickly removed. The worn-out bottom is lowered by a hydraulic jack, located beneath the converter, on to a car which conveys it to the repair room. Meanwhile a new bottom on a second car is lifted into place and keyed on. The new bottom is carefully dried and heated to a high temperature before being put in place, and the joint with the body lining is daubed with mud before the bottom is forced into place by the hydraulic ram.

The blast is derived from blowing engines operating on steam or blast-furnace gas. A pressure of 20 to 30 pounds per square inch is maintained. The turning on and off of the blast, as well as the movement of the converter, is under the control of the blower who stands on a raised platform called the pulpit within full view of the entire operation.

If the Bessemer plant is not operated in conjunction with a blast furnace, the pig iron is melted in cupolas which differ in no respect from the ordinary foundry cupola except in size.

More commonly, the pig iron is run into ladles at the blast furnace, and transferred to the steel plant, where the ladles are discharged into the mixer, which serves as a source of supply for the converters.

The mixer is a large steel reservoir lined with refractory brick and mounted on rollers. Hydraulic cylinders located at the corners serve to tip the mixer to pour out the metal. The capacity of the mixer is from 150 to 500 tons. Because of its large size, the mixer will hold the product of several furnaces, and tends to average the irregularities in the different irons. The mixer also serves to keep the pig iron molten for an indefinite length of time, compensates for delays either at the blast furnace or at the steel plant, and affords an opportunity for the addition of special pig iron, if necessary to correct the composition.

70. Operation of the Acid Bessemer Process. The position of an eccentric type of converter, while receiving its charge, is shown in Fig. 33. The blast is turned on after charging and before righting, in order to prevent the metal from entering the tuyères. The bath of metal occupies only a small portion of the volume of the converter, on account of the increase in volume of the bath caused by the violent ebullition of the metal during the blow.

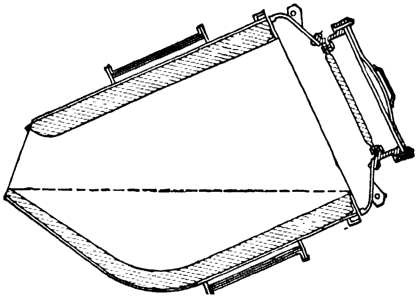


Fig. 33.—Position of Eccentric-type Converter while Receiving Charge.

As soon as the blow is on, the silicon and manganese begin to burn to SiO_2 and MnO and are reduced to mere traces before the oxidation of the carbon becomes appreciable. After two or three minutes, the carbon begins to oxidize and a reddish-yellow flame makes its appearance at the mouth of the converter. This becomes rapidly augmented until a white-hot flame 20 to 30 feet in height pours out with a loud, roaring sound, and a shower of sparks appears. Soon the flame begins to flicker and shorten, indicating that the carbon is practically burned out, whereupon the converter is turned down, the blast shut off, and the recarburizer added.

The phosphorus and the sulfur will not have been affected by the process, but the percentage present in the blown metal will be slightly higher than in the pig iron because of the loss of other elements which have been carried away in the slag.

The total time required for the blow is, in American practice, from nine to ten minutes.

71. Recarburizers and Recarburizing. The principal recarburizers are spiegeleisen and ferromanganese. Spiegeleisen is a special pig iron, high in manganese and carbon. The manganese content varies from 12 to 20 per cent and the carbon from 4 to 6 per cent. Iron alloys containing 20 per cent or more of manganese are classed as ferromanganese, but practically all that used as a recarburizer contains about 80 per cent manganese and 6.5 to 7 per cent carbon. Spiegeleisen is always added in a molten state because large amounts are necessary, and the bath would otherwise be cooled too much before pouring. For this reason small auxiliary spiegel-melting cupolas are a necessary feature of Bessemer plants. Other recarburizing agents which are used include silicon carbide, silicomanganese, silicospiegel, and powdered coal or coke.

72. Deoxidation. The addition of the desired amount of carbon to the blown metal is by no means the only important function served by the spiegeleisen or ferromanganese. Blown metal invariably contains considerable amounts of oxides of carbon and iron. The carbon monoxide gas is somewhat soluble in the molten metal and, even though a great part of it is removed when the spiegel is added, it continues to be evolved until the metal becomes solidified. The imprisoned carbon monoxide means the presence of blowholes in the ingots of steel.

Iron oxide is reduced principally by the manganese of the recarburizer. It is also reduced by the carbon and the silicon of the recarburizing agent.

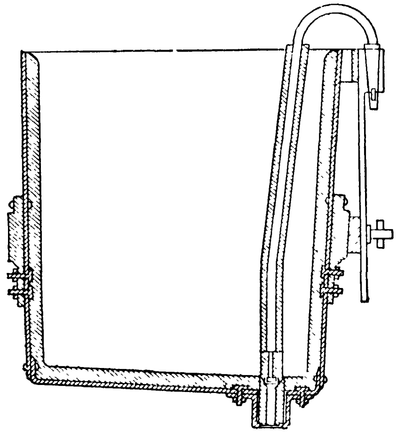


FIG. 34.—Steel Teeming Ladle.

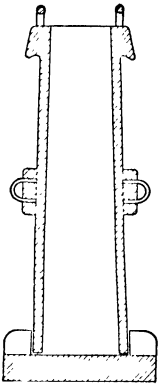


FIG. 35.—Ingot Mold.

The silicon, too, is very effective in reducing the carbon monoxide gas, thereby becoming an important factor in the prevention of blowholes.

Sometimes especially strong deoxidizing agents such as aluminum are used in addition to the recarburizer to eliminate the last traces of oxides in the steel. An important instance of such a practice is the addition of titanium to steel for railroad rails.

73. Casting the Ingots. When the reaction between the blown metal and the recarburizer is complete, the steel is poured from the converter into a teeming ladle which is suspended from a crane. The teeming ladle, Fig. 34, consists of a bucket-shaped steel shell, lined with refractory material and provided with a valve in the bottom through which the molten metal is teemed. The ladle is suspended by a bail and mounted in such a manner that it may be tipped over to pour out the slag which remains in the vessel after the steel has been teemed off. The ingots are cast in cast-iron molds mounted on cars which are moved along a track through the mill. The usual type of Bessemer ingot mold is shown in Fig. 35. The ingot produced is about 7 feet high, has an average cross-section of about 18 by 18 inches, and is about 3 inches thicker at the base than at the top in order to facilitate the stripping off of the mold. Ingots of this type are sometimes cast with the large ends up.

The mold cars are moved along in such a manner as to bring each mold in succession under the nozzle of the ladle. The plunger is raised, allowing a thin stream of metal to flow into the mold, then dropped while a new mold is brought into place. The slag floats on top of the steel, and the valve is closed when slag begins to flow and the ladle is swung over a slag car and dumped.

The mold cars are drawn outside the steel mill, where the molds are stripped off by a crane, which engages the lugs provided on the molds and lifts them off, leaving the ingots standing on the iron stools which form the bottom to the mold. The ingots are then taken to the "soaking pits," while the molds are washed with clay water, allowed to cool somewhat, and run back into the mill for another cast. If the molds are not still hot from a previous heat, they must be heated before being used.

74. The Basic Bessemer Process. The basic Bessemer process differs from the acid Bessemer process only because of the different class of iron used. The basic Bessemer process has not been used to any extent in America but is the principal Bessemer process in Europe. The basic converter differs from the acid converter only in being considerably larger than the acid converter of the same capacity, on account of the increased amount of slag formed, and in having a basic lining. This lining is much less durable than an acid lining, its average life being commonly from 100 to 200 heats, while the bottoms are good for from 20 to 40 heats.

The Pig Iron Used. Basic Bessemer pig iron is high in phosphorus, manganese, and usually sulfur, and relatively low in carbon and silicon. The usual limits of composition are:

Phosphorus, per cent	Sulfur, per cent	Manganese, per cent	Carbon, per cent	Silicon, per cent
1.0–3.0	0.02–0.30	0.3–2.0	2.75–3.5	0.2–1.0

If the phosphorus is not high the charge is likely to blow cold after the elimination of carbon. High manganese is desired to aid the silicon in producing heat at the beginning of the blow, and to facilitate the removal of sulfur which is likely to be high because of the low silicon content.

The relatively low carbon content is an inevitable consequence of the presence of high manganese and phosphorus and low silicon. Only sufficient silicon to prevent too high sulfur is desirable since, with the high phosphorus content, there would be danger of producing an acid slag if the silicon were not kept low. In any event, the amount of lime required to flux the acid-making constituents, phosphorus and silicon, will be increased by increasing the content of these elements.

75. Operation of Basic Bessemer Process. The basic Bessemer process is divided into two more or less distinct stages. The first, called the "fore-blow," is characterized by the oxidation of silicon, manganese, and carbon, and corresponds to the ordinary blow of the acid Bessemer process. The phosphorus and most of the sulfur are removed and absorbed by the slag during a later period called the "after-blow."

Silicon, being low originally, is usually eliminated within 2 minutes or less, but manganese is removed very slowly because a large quantity is present and the slag is not of such a composition as to take it up readily. Often some manganese is left in the iron at the end of the blow and is available for deoxidation.

Carbon is oxidized after the elimination of silicon, the removal being accomplished in slightly less time than in the acid process because of the lesser amount present.

Phosphorus is not materially reduced in amount until the carbon is practically eliminated, when it becomes oxidized and is absorbed by the slag. A certain amount of the sulfur is also absorbed by the slag at this time.

The time required for the conversion process with the basic converter is nearly double that for the acid process. The fore-blow requires from 9 to 12 minutes, and the after-blow from 5 to 6 minutes. There is no indication, so far as the flame is concerned, of the completion of the after-blow, and its timing must be judged entirely by experience.

76. Recarburization. The manner of using a recarburizer in the basic process differs from that in the acid process, because, if the spiegel is added to a bath containing a great quantity of basic slag, the carbon, silicon, and manganese of the recarburizer will reduce phosphorus from the slag and restore it to the metal.

As much as possible of the basic slag is therefore poured out of the converter first, and later, as the metal is poured into the teeming ladle, a further quantity of the slag is held back and retained in the vessel. The recarburizer is then added in the ladle, and its action is thereafter similar to that noted for the acid process. The deoxidizing effect of the recarburizer is no less important in the basic than in the acid process, for the oxidation of iron in the basic converter is likely to be excessive.

77. Comparison of Acid and Basic Bessemer Processes. The acid process necessitates a higher grade of ore and one that is almost unobtainable in some countries. The basic process, upon the other hand, requires a cheap ore to be commercially successful, because the process itself is expensive.

The basic process requires a high degree of skill, because of the danger of excessive oxidation and also the restoration of phosphorus to the bath through the action of manganese in the recarburizer.

THE OPEN-HEARTH PROCESS

78. General. The modern process of steel making by the open-hearth method has been developed from the early work of the Siemens brothers, who invented and patented the regenerative furnace in 1861. Sir William Siemens developed and perfected the early forms of the regenerative furnace, making possible the utilization of this principle in the attainment of the very high temperatures required for the making of steel in the open-hearth process.

The open-hearth process developed more slowly than the Bessemer process, but now ranks first among the various methods of steel manufacture, both in metallurgical perfection and in tonnage produced. It is now used almost exclusively for all except the cheapest grades of steel and some high-grade alloy steels.

The open-hearth process is so called because it consists in the oxidation and removal of impurities contained in a bath of metallic iron lying on the hearth of a reverberatory regenerative furnace, the bath being exposed to the action of the flame which sweeps across above the hearth.

The rate of oxidation is so slow in the open-hearth process that insufficient heat is generated by oxidation to maintain the metal in the bath in a molten condition. Consequently, heat must be applied to the metal during the process. This additional heat is usually derived from the combustion of gas fuel.

The open-hearth process differs from the Bessemer process in the rate of oxidation of the impurities, requiring about 10 hours as compared with about 10 minutes. The furnace capacity is much greater than that of the converter, however, being from 50 to 200 tons.

In America the open-hearth method is conducted either as an acid or as a basic process, but the basic process greatly predominates.

The open-hearth furnace is charged with pig iron (either solid or molten) and scrap steel (always solid), and the operation is started by admitting a current of preheated natural or producer gas and air which burn within the hearth chamber. Much heat is reflected from the arched roof and the walls. A certain amount of ore is added during the process to provide additional oxides, and more pig iron may be added if there is danger of the original carbon becoming low too early in the heat to maintain the required temperature until the end of the operation.

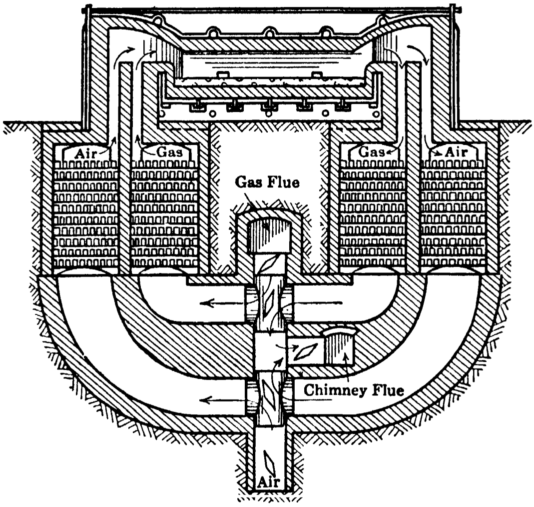


Fig. 36.—Diagram of Regenerative Furnace. (Stoughton.)

The furnace is tapped through a spout either by opening a taphole or by tilting the furnace, the spout in the latter case being located above the normal level of the bath of metal.

79. The Furnace and Its Operation. The great difference in principle between the puddling furnace and the air furnace on the one hand, and the open-hearth furnace on the other hand, lies in the utilization by the latter of the regenerative principle with gas fuel. By preheating the gas and the air used for combustion, by means of the heat carried out of the melting chamber by the burned gases, a great increase in thermal efficiency is gained and the furnace temperature attainable is immensely increased.

The arrangement of a furnace to utilize the regenerative principle is shown by the diagram of Fig. 36. The melting chamber, or hearth, is shown in the upper central portion of the figure. On either side are the openings called "ports," through which the gas and air enter the melting chamber, and the vertical flues which lead to the regenerative chambers. Two regenerative chambers, or "regenerators," are provided on each side of the furnace, the larger and outermost one preheating the air required for combustion and the smaller inner chamber heating gas. Each regenerator is filled with a checkerwork of brick through which the gas and air pass. Before a cold furnace is started up, these regenerators are heated by fires built in the flues beneath.

By reversal of the valves the direction of flow of the air and gases may be reversed, so that, as soon as one set of regenerators begins to be cooled too much, the incoming gas and air may be sent through the other set, which has just been heated by the burned gases. By reversing the direction of the currents about every 20 minutes the temperature of the melting chamber may be maintained at a fairly constant point, in the neighborhood of 1600° C. (2912° F.) to 1700° C. (3092° F.).

The two common forms of the open-hearth furnace, both of which find wide application in the steel industry, are the stationary furnace and the tilting or rolling furnace.

Stationary Open-hearth Furnace. The melting chamber is a rectangular structure built of brick masonry and supported upon either a solid masonry foundation or on beams and piers. It is reinforced with buck stays, bearing plates, and tie rods, and is lined with refractory material of suitable chemical nature to resist the attack of the materials which come in contact with it. The hearth is built in the form of a shallow dish and has a capacity of 15 to 200 tons of metal.

If the furnace is intended for the acid process, the hearth is built of fireclay bricks overlaid with a layer of silica about 18 inches thick. The silica is applied as silica sand, which is spread in thin layers, each layer being exposed to the full heat of the furnace and brought to the sintering point before the application of the next layer.

The basic furnace is built of magnesite bricks overlaid with a mixture of calcined magnesite and about 10 per cent of anhydrous tar. The lining is placed in layers and burned in place as in the acid furnace.

One or more large charging doors are provided in the front wall of the furnace just above the level of the top of the hearth lining, and an inclined spout leads from the lowest portion of the hearth to the back or pouring side of the furnace.

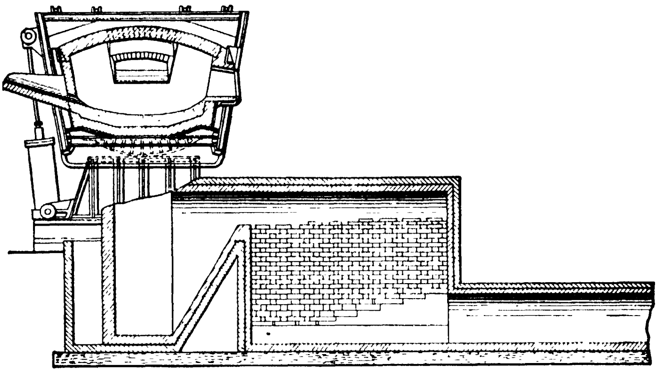
The side walls of the melting chamber and the arched roof are made of silica bricks, the most refractory material that can be obtained, laid with almost no mortar in the joints. The roof is arched from front to back and its skewbacks are supported upon steel channels, which practically carry the weight of the roof independently of the side walls. In lining the basic furnace a layer of neutral chromite brick is usually placed between the silica bricks of the side walls and the basic hearth.

The ports are designed with great care in order that the flames may impinge neither upon the bath, thereby oxidizing it excessively, nor upon the roof, which would quickly be burned out. The gas ports are always located beneath the air ports, in order that the bath may not be oxidized excessively by direct contact with the air, and also to promote a better mixing of gas and air, since the gas is lighter and therefore rises. The masonry of the ports is built of silica bricks and the floor is commonly covered with a layer of neutral chrome ore. The port area required for air is about twice that required for gas.

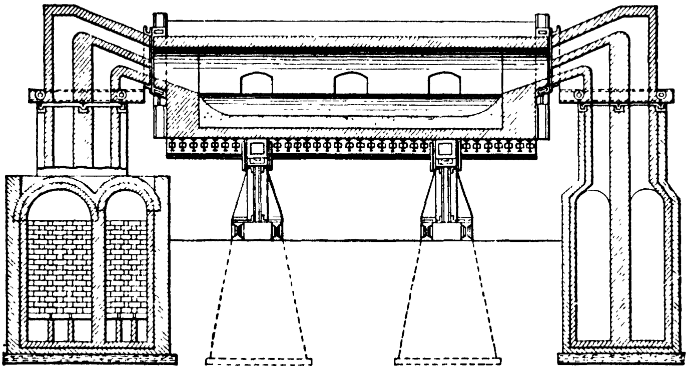
In order to prevent the carrying of dust and slag into the regenerators, the vertical flues from the ports do not lead directly to the regenerators, but to chambers called *slag pockets* which are located on a level with the regenerators below the melting chamber.

The regenerators are very large in proportion to the melting chamber, and are nearly filled with the checkerwork of bricks which serves to absorb heat from the outgoing gases and preheat the incoming gas and air.

Tilting or Rolling Furnace. A furnace of the tilting or rolling type is shown in Fig. 37. The furnace consists of a heavy steel casing of rectangular form, lined with masonry like the stationary furnace, but mounted on two steel rockers which rest upon heavy bed-castings. Two large hydraulic cylinders on the pouring side of the furnace serve to rock the furnace forward or backward during the operation of pouring.



(*a*) Transverse Section.



(*b*) Longitudinal Section.

Fig. 37.—The Wellman Tilting Open-hearth Furnace.

The design and arrangement of the slag pockets, regenerators, valves, and flues for the rolling furnace differ in no essential respect from those of the stationary furnace above described.

80. Stationary vs. Tilting Furnaces. The stationary furnace is less complicated in its design and requires less elaborate equipment for its operation. It is less expensive to install, and the cost of its upkeep is much less. On the other hand, the tilting furnace has the advantage of never causing delay and consequent oxidation of the bath, owing to difficulty in clearing the taphole; the slag can be poured off at any time, which is a great advantage in the basic furnace especially; repairs to the hearth bottom may be made with much greater facility between or even during heats; metal may be poured off at any time and transferred between furnaces; and boiling and violent action during pouring are lessened by the chilling of the metal caused by the entrance of cold air through the open ports.

81. Life of Furnace and Repairs. The life of the open-hearth furnace is extremely variable, depending upon the quality of the materials of which it is made and upon its management. The ports are usually the first portion to become excessively injured and often need replacement long before the furnace must be entirely rebuilt. The removable ports of the tilting furnace have a special advantage on this account.

The bottom usually requires repairs in spots between heats, and is more extensively repaired during temporary shutdowns. In this way the bottom lasts almost indefinitely.

The roof of the furnace fails sooner or later by burning through in spots or by falling in. When this happens the furnace must be practically rebuilt.

The regenerators finally give out, either by becoming choked up with dust, or by cracks opening up in the walls. A shutdown is required in either event.

In general the life of a furnace is from 200 to 600 heats, or from 3 to 6 or 8 months' operation. The acid furnace lasts longer, from 800 to 1200 heats, or from 10 to 16 months.

82. The Basic Open-hearth Process. The basic open-hearth process, like the basic Bessemer process, differs from the acid process mainly in that it utilizes stock higher in phosphorus and sulfur, and a basic slag must be produced by the addition of strong bases to the charge in order to effect the removal of this excess phosphorus and sulfur.

Basic open-hearth practice is characterized by a number of quite distinct modifications, depending upon the choice of materials which constitute the furnace charge.

The pig iron may contain anywhere from a small quantity up to 2½ per cent phosphorus, less than 1 per cent of silicon, and at least 1 per cent of manganese. The carbon will usually run from 2.5 to 3.5 per cent. The pig iron may be charged either solid or molten.

The substitution of scrap iron for pig iron results in shortening the time required for the operation, since there will be a lower percentage content of impurities to eliminate. When the pig iron is entirely replaced by scrap, insufficient reducing material is present to prevent excessive oxidation of the iron in melting, and it becomes necessary to supply carbon in some form as a reducing agent.

In the "pig-and-ore process" the charge is principally pig iron, to which ore is added in order to hasten the process. The limiting amount of ore is reached when the boiling of the charge becomes excessive. Unless pig iron is cheaper than scrap, the pig-and-ore process is not commercially practicable. Molten pig iron is often used in this process, the iron being poured in on the ore, which has first been charged. A mixer is commonly interposed between blast furnace and steel furnace as in the Bessemer process.

The "pig-and-scrap" process is the most common, the average practice being to use about 50 per cent of each material, the exact proportions in a given charge being largely a question of relative costs. Very often a small proportion of ore or mill scale is added to hasten the process.

The flux is commonly lime, the amount required being dependent upon the contents of phosphorus, sulfur, and silicon in the charge.

Melting on the basic hearth is attended by oxidation of the metalloids, the most easily oxidized ones being eliminated first. The silicon, manganese, and carbon are all considerably reduced in amount during the period of melting (the first 4 or 5 hours). The phosphorus, however, remains practically unaffected until the end of this period, when it begins to be oxidized rapidly.

It is necessary, in order to prevent the bath from becoming too cool and to prevent oxidation of the iron toward the end of the operation, to eliminate the carbon last. If the carbon is disappearing too early it is the practice of the melter to add pig iron to provide additional carbon. Sometimes, when the phosphorus burns out rapidly and the carbon too slowly, it is necessary to hasten the oxidation of carbon by adding ore. The progress of the operation is tested from time to time by ladling out a small amount of metal, casting a small test billet, breaking it, and examining the fracture. Billet tests are usually supplemented by chemical analysis of frequent samples.

The slag performs several very important offices in the operation of the basic hearth. Its chief function is to take up and retain the oxides of silicon, manganese, phosphorus, and sulfur. It must also act as a protection to the bath from excessive oxidation by the furnace gases, and, by virtue of its contained oxides, assist in the oxidation of the impurities. For efficient action as a deoxidizing agent it must be very fluid in order that it may mix intimately with the bath.

83. Recarburization. Recarburization of basic steel cannot be accomplished in the furnace because the carbon, silicon, and manganese of the recarburizer would reduce the phosphorus in the slag and restore it to the metal.

On this account the recarburizer, in the form of ferromanganese, together with coal, charcoal, or coke, is added to the stream of metal as it flows into the ladle. Provision is made for the removal of the greater part of the slag by overflowing at the top of the ladle. Spiegeleisen is not used as a recarburizer, because it must be used in a molten state and a cupola could not be operated to supply it in proper condition at the infrequent intervals at which a recarburizer is required in open-hearth operation.

84. Pouring the Ingots. The steel is discharged from the pouring spout or taphole of the furnace into a teeming ladle or fore-hearth, from which it is teemed into ingot molds mounted on cars. The ordinary open-hearth ingot may weigh 10 tons or more and is, therefore, much larger than the usual Bessemer ingot.

85. The Acid Open-hearth Process. The acid open-hearth process differs from the basic open-hearth process principally in the kind of iron used, the omission of the flux, and the time required for the operation. Since the slag formed is acid, it is unable to retain oxides of phosphorus and sulfur, and a pig low in these elements is required. Thus the limits of composition of the charge are more restricted in the acid than in the basic process. An acid lining of the hearth is necessary to prevent rapid corrosion by the acid slag. The time required for the operation is shorter than that for the basic process as the iron contains less impurities to be removed, and because no part of the heat is consumed in melting and accomplishing the function of the flux.

The charge of the acid furnace usually consists of approximately one-third pig iron and two-thirds scrap. The pig iron is fairly low in silicon, and low in manganese, phosphorus, and sulfur. The usual limits of composition are from 0.8 to 2.0 per cent silicon, 0.3 to 0.5 per cent manganese, and less than 0.05 per cent of both phosphorus and sulfur. The carbon content is from 3.0 to 4.0 per cent.

Ore is not usually initially charged in the acid furnace, but may be added during the process to hasten the removal of carbon. The pig iron is charged into the furnace before the scrap in order to prevent the scorification of the hearth, which would occur if scrap were charged first.

The melting operation is in the main an oxidizing action, though the flame may be a comparatively reducing one during charging in order to prevent excessive oxidation of the pig iron and, more particularly, the scrap during this stage.

The metalloids are largely eliminated during the melting-down stage, which requires some 3 to 4 hours, the silicon usually disappearing first, closely followed by the manganese. The amount of carbon oxidized during melting is dependent largely upon the amounts of the more easily oxidized elements (silicon and manganese) present. The lower the content of the latter elements, the greater will be the proportion of carbon oxidized. In any event, two-thirds of the carbon will be removed very soon after the charge is completely melted. The balance will be oxidized only very slowly, its disappearance usually being accelerated by the addition of ore to the bath. The slag in the acid process never constitutes the important oxidizing agency that it does in the basic process.

86. Recarburizing. Recarburizing in the acid process is accomplished in the furnace, rather than in the ladle, because the considerations which prevent recarburization in the basic furnace are not operative here. The practice as to the degree of recarburization varies, but in general the carbon is reduced to the practical minimum for mild or medium steel, and the recarburizer added 20 to 40 minutes before the heat is tapped. In melting for high-carbon steel the carbon is usually reduced only slightly below the desired amount before the recarburizer is added. In this event, the addition to the bath is rather more a deoxidizer than a recarburizer. The recarburizer or deoxidizer is, in this process, ferromanganese and ferrosilicon, as a rule. Coal is sometimes added in the ladle as in the basic process. The addition of the recarburizer necessarily largely increases the content of silicon and manganese in the steel, as well as the carbon content.

87. Comparisons of Bessemer and Open-hearth Processes. The Bessemer process has the following advantages as compared with the open-hearth process: the operation is comparatively simple, the conversion period is short, no fuel is required, and the plant cost is small per unit of output.

The open-hearth process has a small conversion loss, the heats are relatively large, more accurate control of the product is possible, and in the basic process considerable variation in the composition of the materials of the charge is permissible. Open-hearth steel is usually of better quality than Bessemer steel. Under proper conditions of operation an excellent grade of steel can be produced by the acid open-hearth process.

88. Duplex Processes. There are several methods by which the acid Bessemer and the basic open-hearth processes may be combined in a so-called "duplex process," whereby the silicon, manganese, and part of the carbon are eliminated in the converter, the phosphorus and the remainder of the carbon being removed in the open hearth.

In one duplex process the pig iron is blown in the acid converter until the silicon and manganese are practically eliminated and the carbon reduced to about 1 per cent, after which the converter charge is transferred to a mixer and thence to the basic open hearth, wherein the phosphorus and the remainder of the carbon are removed.

In another method the Bessemer blow is continued till the carbon is reduced to only a few tenths of 1 per cent, after which the product is transferred to the open hearth, mixed with a large proportion of pig, generally molten, and the process completed exactly as in the latter part of the ordinary pig-and-scrap process.

The advantage of the duplex over the Bessemer process lies in the fact that lower-grade, high-phosphorus pig iron may be used and yet produce a satisfactory grade of open-hearth steel.

The advantages of the combined over the open-hearth process are the saving of about one-half the time ordinarily required in the open-hearth, and the saving effected in cost of renewals of the hearth lining, because of the fact that the silica is removed before the metal enters the hearth.

ELECTRIC REFINING OF STEEL

89. Electric Refining Processes in General. The part which electricity plays in electric steel-refining processes is simply that of a source of heat. Electric furnaces for refining steel may be of either the arc or resistance type. Historically, the arc type of furnace may be traced from Davy's experiments with Volta's battery in 1800 in which an arc was produced between carbon points. The principle of the resistance furnace was developed by Pepys in 1815 by his experiments on heating an iron wire to a red heat by passing an electric current through it. The invention of the dynamo made possible increased experimentation and use of electric furnaces for steel making.

The main use of electric furnaces is in the production of alloy steels and of highly refined steel from steel scrap and Bessemer and open-hearth-process steels.

90. Electric Steel-refining Furnaces. Electric furnaces have hearths constructed of steel plates and lined with refractory materials. Electrodes are inserted through holes in an arched roof of firebrick. Doors for charging and a taphole for drawing off the refined steel are provided. The tilting type of furnace is in common use since the operations of tapping the steel and drawing off the slag are more conveniently handled than in the stationary type. The hearth in the basic process is lined with burned magnesite or dolomite and is bonded with tar. Acid hearth linings of silica are sometimes used in steel foundries where the furnace merely reheats the steel without removing any impurities.

Three quite distinct types of electric steel-refining furnaces have been developed to the point of practical commercial application.

1. Furnaces employing an open arc between electrodes above the bath,

the bath being heated by radiation alone. Owing to radiation losses of the arc to the roof, this type is not so popular as the other types.

2. Furnaces employing an arc between electrodes and the bath, the bath forming a part of the electric circuit. The metal is heated largely by conduction from the slag bath, which carries much of the current and is heated both by radiation and by reason of its electrical resistance. The Héroult furnace is typical of this type and is the most extensively used electric steel-making furnace. The arcs are operated in series, and hence this furnace is known as a series-arc type. Three-phase alternating current and three electrodes are commonly used.

.3. Electric induction furnaces, wherein the bath forms the secondary of a transformer. The transformer consists of a primary winding of insulated copper wire of many turns, a core of laminated iron sheets, and a closed circuit with but a single turn which is the metal in the bath. Metal must be placed in the secondary in starting up the furnace, and at the end of a heat some of the metal is left in the furnace to form the secondary circuit.

Current is usually brought to the furnace at high voltage and transformed into a current of low voltage and high amperage. Automatic devices are commonly provided to control the rate of heating by regulating the distance between the electrodes and the metal in the bath.

91. Basic Electric Refining Process. Slags, which are strongly oxidizing, must be added to the bath in order to effect any refinement. In practice, the slag is a strongly basic iron oxide slag, because such a slag will oxidize phosphorus as well as retain the oxide formed. If much phosphorus is to be removed, or if it is to be reduced to a very low point, it is necessary to use two slags, skimming off the first after it becomes highly phosphorized.

Sulfur can be reduced only by removing the iron oxide slag, after the elimination of phosphorus, and producing a slag that is made up almost entirely of lime. The presence of manganese favors the removal of sulfur, because manganese sulfide is more readily taken up by the slag than iron sulfide, thus making possible the formation of calcium sulfide, in which form the sulfur is retained in the slag.

Recarburization is accomplished by adding carbon or ferromanganese to the steel in the furnace after the slag has been removed.

One of the greatest advantages of electric refining processes lies in the fact that dissolved gases, occluded oxides, etc., are readily removed from the steel through the agency of heat alone.

92. Applications and Limitations of Electric Refining Processes. The electric furnace is able to make tool steel of crucible quality at a lower cost than the crucible process. In the field of steel castings it has also a considerable advantage over the highest-grade crucible-made castings in the matter of cost, though it cannot compete with the open-hearth process in the production of lower-grade castings.

The electric furnace is not a competitor of the Bessemer converter and the open-hearth furnace in the production of mild and medium steel of ordinary quality. It is an important adjunct of both these processes, however, taking their product and superrefining it to produce steel for special purposes.

In the production of special alloy steels, the electric furnace has a special advantage over other steel processes in that it need not be operated under oxidizing conditions, but may be worked under either neutral or reducing conditions. This is an important consideration in using certain valuable alloying elements which are very easily oxidized and lost in other furnaces.

Rolling Mill Operations

93. General. An ingot cannot be sent to a rolling mill and rolled immediately after the ingot mold has been removed, because at that time the interior is still molten. If, on the other hand, the ingot is allowed to stand until the interior has solidified, the exterior will be too cold to be worked. It is therefore necessary to place the ingots, immediately after stripping, in a furnace or pit where the interior may be solidified and the exterior kept at the required temperature for working.

The process of rolling finished steel sections from ingots requires many passes of the metal through the rolls. It is necessary, at one or more stages in the reduction of the section, to reheat the bloom or billet or slab which has been formed by the initial reduction of the ingot, when it has cooled below the proper working temperature.

Two classes of reheating furnaces are therefore a necessary part of the equipment of a rolling mill: first, a furnace for heating ingots, or at least equalizing their temperature, and second, a furnace wherein billets or unfinished shapes may be reheated at any stage in the rolling process.

94. Reheating Furnaces. There are three principal classes of reheating furnaces: the "soaking pit," the regenerative gas-fired pit-furnace for ingots, and continuous furnaces for billets and other small sections. Special types of reheating furnaces are also required for reheating large blooms and slabs.

The soaking pit is a masonry chamber, built below the floor level, and charged through the top in order that the ingots may remain vertical while solidifying. No fuel is employed, but the ingots are stripped and placed in the soaking pit as soon as possible after teeming, the heat of the still molten interior of the ingot being depended upon to bring the exterior to the proper temperature.

The regenerative gas-fired pit-furnace is also a vertical furnace, built below the floor level, and charged through the top. Gas fuel is burned within the heating chamber.

Billet-heating furnaces are now commonly of the reverberatory type, gas-fired, and recuperative in principle. The billets are charged at the cool end of the furnace, and are pushed along through the length of the furnace by a hydraulic ram mounted at the charging end. Water-cooled pipes laid in the bed of the heating chamber and extending throughout its length provide a sort of track along which the billets are pushed. The billets encounter hotter temperatures as they approach the end where the gas and air ports are located, and are there discharged and conveyed back to the rolls. The burned gases, upon leaving the heating chamber, are caused to pass through a series of pipes in a chamber below the working chamber, and the air which is to be used for combustion is caused to circulate through this chamber, thus becoming preheated.

95. Rolling Mills. The most essential parts of a rolling mill are the rolls. Cast-iron rolls, which have been chilled to produce a hard exterior, and turned in a lathe to produce a smooth surface of the desired form, are very commonly used, especially for finishing rolls. High-carbon and alloy steels are also used. All the rolls except those for finishing have their surface roughened in order to increase their grip on the metal.

Rolls are turned in a great variety of shapes, varying from the plain cylinders for plates and some rectangular shapes to the rolls for structural shapes, rails, corrugated bars, etc., which may be quite intricate in form. All rolls except plain cylindrical rolls make provision for several passes of the metal, each pass approximating the final form of the section desired more closely than the last.

Rolling mills may be in general classed under one of three heads: "two-high" mills, "three-high" mills, and "universal" mills.

Two-high mills consist of a single pair of rolls mounted in the same vertical plane. One variation of the two-high mill is the "pull-over" mill, whose rolls always run in the same direction, so that the metal after each pass must be pulled back over the top of the rolls to be fed in for the next pass. This is the simplest form of mill and the cheapest, but its operation is slow, and it is adapted only for rolling small shapes which can be readily handled. A more important type of two-high mill is the "reversing" mill, the rolls of which may be made to run in either direction by reversing the engines which drive them. Successive passes are therefore made in opposite directions through the rolls. The two-high reversing mill is often used in "cogging" ingots.

The *three-high mill* has three rolls geared together, so that the metal may make one pass between the lower and the middle roll, and the next pass in the opposite direction between the middle and upper roll, without reversing the rolls. A very large proportion of all steel shapes are rolled or at least finished by a three-high mill.

The *universal mill* is provided with two auxiliary rolls mounted vertically just in front of the horizontal rolls. The distance between the axis of these rolls is adjustable horizontally, and they are designed simply to keep the edges of the metal smooth without effecting any reduction. Universal mills are made with vertical rolls on only one side of the horizontal rolls or on both sides, and they may be either two-high or three-high mills.

All rolling mills that handle anything except very light material must be provided with a series of rollers in front of and behind the rolls, known as the "roll tables." The roll tables for three-high mills must be capable of being raised or lowered at the end next the rolls, in order that the metal may be directed between either the upper or the lower set of rolls.

96. Examples of Rolling Practice. *Steel Rails.* The ingot, after reheating in a pit-furnace, is cogged down to a bloom the cross-sectional dimensions of which are about one-half those of the original ingot. This operation is accomplished by a series of about 8 or 10 passes through a set of cogging rolls. The bloom is now sheared at each end to remove the pipe and the ragged end formed by the rolls, cut in two, returned to the reheating furnace, and brought again to the proper temperature for rolling. The next series of 4 to 6 passes are made in one or more trains of roughing rolls, and the last 8 or 10 passes in a train of finishing rolls. (The figures given here are merely representative of average practice. The number of passes in each roll train varies considerably in the different rail mills.)

Structural steel sections are rolled in the same manner as rails. The different sectional areas for a given size of any structural shape, such as angles, I-beams, and channels, may be produced with the same set of rolls by simply changing slightly the axial distance between the finishing rolls.

Plates are cogged from the ingot. The resultant slab is sheared into smaller slabs, and the pipe discarded, the slabs are reheated, and the rolling completed. The successive reduction in the thickness of the plate is accomplished by bringing the rolls slightly nearer together between passes. Plates that are rolled in an ordinary mill and then sheared are known as sheared plates. Plates rolled in a universal mill are known as universal mill plates.

Rods are rolled in a manner similar to that described for steel rails except that the original bloom is usually cut up into a number of small sections before reheating and rolling. A mill called a guide mill is used, the material after each pass being bent around and guided into the next pass by a device specially attached to the mill for the purpose.

Wire-making is only a rolling operation so far as the making of the wire-rod is concerned. A considerable portion of the reduction of the section is accomplished by a special operation known as cold-drawing. The wire-rod is rolled in the manner above noted, its final diameter being usually from ¼ to ½ inch. The wire-rod is then wound into coils and pickled in a dilute solution of sulfuric acid, which removes the scale. Water is next sprayed on to wash off the acid, and this is followed by immersion in a bath of limewater, which removes the last traces of acid. The coils are now dried in an oven and sent to the wire-drawing mill.

Cold-drawing consists in successively reducing the section, and extending the length, by repeatedly pulling it cold through tapered holes in a die or "draw-plate." Each hole through which the metal is drawn is somewhat smaller than the preceding hole, the average amount of reduction being from 20 to 25 per cent. Some thick lubricant is applied to the draw-plate to reduce friction and prevent too rapid wear on the hole.

The wire must be annealed by heating to a low red heat in a closed receptacle after each 3 to 10 passes, because of the hardening of the metal caused by drawing. The finished wire is also annealed unless it is to be sold as hard-drawn wire.

Lap-welded Pipes. The metal is first rolled into flat strips called "skelp," of the desired thickness, then bent to a U-shaped section and, by another pass, to a circular section with the edges overlapping. (Small pipe may be bent to the circular section by drawing the skelp through a die.) The metal is now brought to a welding heat and is passed through a pair of welding rolls over a mandrel which is supported between the rolls on the end of a long rod. A second pass through sizing rolls is made to insure accuracy of size.

Butt-welded pipes are made by drawing the skelp at a welding heat through a die or "bell" which welds the edges together without lapping.

Seamless tubes are made either by forcing a flat plate through a cylindrical die by means of a mandrel, or by piercing a billet longitudinally, expanding the hole by forcing larger and larger tapered expanders through it, and finally rolling over mandrels until the section desired is attained.

Cold-rolled steel is steel where the last few passes through the rolls are made with comparatively cold metal. Pickling is necessary before cold-rolling to remove the scale, the result being a great gain in accuracy in size and form, and in surface finish.

97. Mechanical Work. Steel is said to be mechanically worked when it undergoes the operations of forging, rolling, or drawing. If the operation is carried out above the critical range the steel is *hot-worked* and if below the critical range *cold-worked.*

Forging under the Steam Hammer. In the early days of the steel industry the steam hammer was the principal means whereby steel ingots were worked up into the desired final form; but as ingots became larger and heavier, the hammer was to a great extent replaced by rolls which, although they do not work the metal so well, are much more rapid in operation and involve less expense for labor and for reheating.

The steam hammer now finds little application in the steel industry except in the forging of high-grade steel, where the value of the product and the especial desirability of giving the metal the fine grain attained by hammering justify the higher cost, and in the production of that large class of articles called "drop-forgings." This class of articles includes a great variety of machine parts, small tools, automobile parts, etc.

Drop-forgings are made by the use of dies between which the metal is worked into the desired form by the blows of a steam hammer. The dies are made of hardened steel, the impressions formed in the faces of the dies corresponding to the impressions formed in the mold for a casting. The metal is placed upon the lower die, which is made fast to the anvil, and the upper die is carried by the head of the hammer. Very often a series of dies are necessary to complete a forging, each set approximating more closely the final form required.

Pressing. The effect of pressing steel, by the action of large hydraulic presses, differs from that produced by the action of a hammer, in that the force applied acts for an appreciable interval of time, and the distortion produced extends deeper into the metal. In consequence, the press produces a better crystalline structure than the hammer for all except very thin sections, and is therefore preferred to the hammer for all heavy forging.

The hydraulic press consists essentially of a hydraulic cylinder in which a plunger or ram moves vertically, and is forced down upon the metal supported on an anvil block or bed as for hammers. Presses vary in size from a few tons capacity up to 14,000-ton armor-plate presses which will handle ingots weighing 50 tons or more.

Hydraulic presses are used to a great extent not only in the reduction of ingots in place of a cogging mill, and in the pressing of heavy plates, but also in the production of forgings pressed between dies, as in the case of the steam hammer, and in the production of a large class of articles made of thin plate steel which is pressed cold between dies.

98. Effects of Hot Mechanical Working. The first effect of hot mechanical working is the benefit derived from the elimination of flaws, blowholes, etc. The coarse crystalline structure of steel slowly cooled from a high temperature is also improved by working, since the crystals become broken up and mixed intimately, the continuity of their cleavage planes thus being destroyed and their cohesive and their adhesive power being increased.

The amount of reduction necessary in rolling or forging the finished section from the ingot is dependent on many variable factors. It is a fact recognized in the ordinary practice of steel mills, however, that the finished section should never be more than 10 per cent of the ingot section, and it is commonly not more than 2 or 3 per cent, often being much less than 1 per cent.

The temperature at which working is finished ("finishing temperature") is a very important consideration, since, if this temperature is much above Ar_3, the crystals grow to a certain extent, thus diminishing strength and especially lowering the elastic limit of the steel. In the ordinary practice of rolling structural steel, the finishing heat is above Ar_3 and the elastic limit is therefore comparatively low. If the working be continued until the metal is not above Ar_3, large crystals cannot reform, and strength and especially the elastic limit are increased. The lower the finishing temperature, the better the effect of mechanical work, so long as Ar_3 is not passed.

99. Effects of Cold Mechanical Working. Cold-working of steels, i.e., the mechanical distortion of the metal below the critical range of temperatures, cannot be practiced except with low- or medium-carbon steels. The effect of cold-working upon the existing structure is to elongate the crystalline elements in the direction of working. Cold-working does not improve the crystalline structure as does working above the critical range, and the primary effect of cold-working upon physical properties is a marked decrease in ductility and an increase in hardness and brittleness. One other effect, which constitutes a great practical advantage for steels used for certain purposes, is the very material extent to which the elastic limit of steel may be raised by cold-working. This fact is taken advantage of in the manufacture of certain grades of hard wire and in the finishing of steel rods intended for particular purposes. The extent of the effect of cold-working is directly dependent upon how far below the critical range working is continued, and is most marked when working is done at atmospheric temperatures.

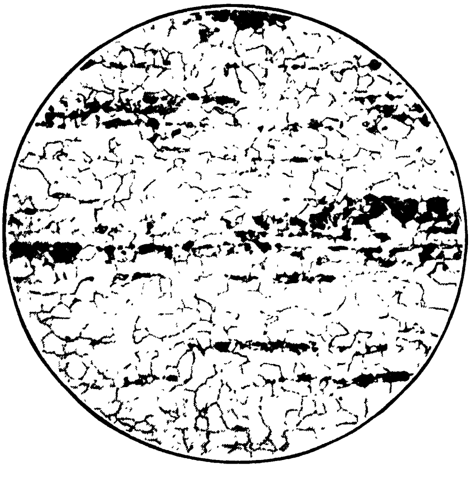


FIG. 38. — Bands of Pearlite in 0.15 Per Cent Open-hearth Steel Cold-worked and Annealed at 843° C. (1550° F.) 100×. (Courtesy of C. L. Clark.)

Cold-working breaks up and distorts the crystalline grains. The grains will remain deformed if kept below the temperature of recrystallization, but, if "annealed" (Art. 109) at a temperature slightly higher than the critical temperature, a "rebirth" of the grains occurs and they become equiaxed.

Banded Structure. In cold-working hypoeutectoid steel, the ferrite grains may become elongated and bands of distorted pearlite grains formed parallel to the direction of cold-rolling. The ferrite grains may be recrystallized by annealing, but the bands of pearlite grains are not changed, as may be seen in Fig. 38. Steel with banded structure has pronounced directional properties.

100. The Slip-interference Theory. The hardening and increase in elastic limit of metals by cold-working can be explained by the slip-interference theory of Jeffries and Archer.* This theory states that, during the motion of slipping, the grains are broken down into thin plates whose surfaces tend to gouge into each other, causing increased resistance. Also slip planes in different crystalline grains have different orientations so that slip in one grain interferes with slip in adjacent grains. Cold-working tends to increase the number of points of contact and thus hardens the metal and raises the elastic limit. This theory explains why slipping stops after a time when the metal is subjected to a stress above the elastic limit.

In metals containing hard crystals interspersed in softer ones, the hard crystals act as "keys," tending to reduce movements along slip planes in the weaker grains. The size of these hard crystals is important. With large crystals, many slip planes would not be intercepted. For extremely small particles, resistance is small because slipping can take place past the particles without much change in path. For small grains of "critical" size, the movement along slip planes is restricted to an optimum degree.

101. Defects in Ingots and Their Correction. *Blowholes.* One of the greatest sources of trouble for the steel-maker is the occurrence of blowholes, which are almost unavoidably formed in some degree while the metal is solidifying in the ingot mold. Blowholes are caused by the presence of gases, such as hydrogen, nitrogen, and oxygen, which are held in solution by the metal when molten but released as the metal solidifies, and they are also caused by the presence in the metal of iron oxide, which, upon encountering carbon, forms carbon monoxide gas.

The gas in blowholes is usually reducing in effect, and therefore the surfaces of the holes do not become oxidized and will weld together when the ingot is subjected to pressure in the operation of rolling or pressing. Blowholes near the surface of an ingot, however, are likely to break through to the exterior, allowing oxidation, preventing perfect welding in the rolls, and producing "seamy" steel.

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* Jeffries and Archer: "The Science of Metals." McGraw-Hill Book Co., Inc., 1924.

Pipe. Another defect in ingots, which cannot be corrected in rolling, is the occurrence of the pipe or shrinkage cavity which forms during solidification. Since the metal cools first in contact with the walls of the mold, the interior will remain molten after an outside solid shell has formed. The interior metal contracts as it solidifies progressively from the outside inward, causing the formation of a cavity which becomes filled with gases evolved during solidification. Since the hottest metal is at the top of the ingot, the upper portion remains molten longer and acts as a feeder to fill the shrinkage cavity in the bottom portion. The pipe is thus localized in the upper third of the ingot. This portion must be cut off in the rolling mill, and it goes back to the steel furnace as scrap.

FIG. 39.—Macro-etch Showing Dendritic Structure. Etched with Stead's Reagent. (Homerberg.)

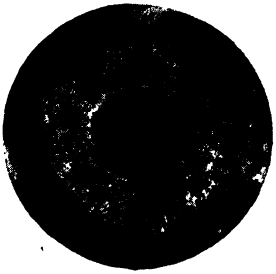

FIG. 40.—Macro-etch Showing Phosphorus Segregation in Steel Bar. Etched with Iodine. (Homerberg.)

Ingotism, the formation of large crystals of steel, caused by too slow cooling or casting at too high a temperature, is a serious defect in ingots which causes the steel to be weak and low in ductility. The bad effects of ingotism may be largely or entirely corrected by careful rolling or forging. The compression of the metal crushes and reduces the size of the crystals, imparting to the steel a much superior degree of strength and ductility. Care must be taken in the initial rolling or forging to avoid the formation of cracks which cannot subsequently be welded up.

Segregation of the impurities in steel ingots is caused by the fact that most impurities, notably carbon, phosphorus, and sulfur, are less soluble in iron when solidified than while molten. In consequence, a part of the impurities in the iron are progressively rejected by each layer of metal as it solidifies, being absorbed by the still molten portion, the net result being a tendency toward concentration of the impurities in that part or parts of the ingot which solidify last. Segregation cannot be altogether prevented, but it may be lessened by the addition of elements such as aluminum or titanium, which have the effect of quieting the steel. Casting in narrow ingots is also effective, but is not always practicable because it would take so long to cast many small ingots from one large ladle that the first metal would be too hot if the last metal were not too cold.

102. Dendritic Structure. During the crystallization of steel, elongated crystals known as "dendrites" are many times formed (Fig. 39). The growth of dendrites in steel is associated with the segregation of phosphides and possibly sulfides and oxides. During hot-working, the dendritic structure is rolled into ribbons, in hypoeutectoid steel, banded structures are formed which when suitably etched and viewed under the microscope have phantom-like structures called "ghost lines." These ghost lines are lines of ferrite with small inclusions of impurities (Fig. 40). Carbon is probably expelled from these bands by the action of segregated phosphorus. The formation of such dendritic lines affects the directional properties of steel since the tensile strength is reduced across the bands.

STRUCTURE AND CONSTITUTION OF IRON AND STEEL

103. The Iron-carbon Equilibrium Diagram. The iron-carbon equilibrium diagram shown in Fig. 41 gives essential information concerning the constitution of iron, steel, and cast iron. It might more properly be termed the iron-iron carbide diagram since it is generally considered that the carbon exists in the stable phase as iron carbide, Fe_3C, which is called *cementite*. The equilibrium diagram shown in Fig. 41 is plotted for amounts of carbon up to 5 per cent, which is sufficient for practical purposes. The diagram is sometimes shown extended up to 6.67 per cent carbon, which corresponds to 100 per cent cementite, since 1 per cent carbon corresponds to 15 per cent cementite.

104. Classification of the Ferrous Alloys. Alloys containing very small amounts of carbon (not exceeding 0.008 per cent) are classed as *irons;* alloys in which the carbon ranges from small amounts up to the point of maximum solubility in iron (up to about 1.7 per cent) are usually classed as *steels;* while the iron alloys containing above 1.7 per cent carbon are usually classed as *cast irons.* A further subdivision may be made in which those steels having less than 0.83 per cent carbon (the eutectoid composition) are known as the *hypoeutectoid* steels while those varying in carbon content from 0.83 per cent up to 1.7 per cent are called *hypereutectoid* steels. A similar division is made in the iron class. Irons from 1.7 per cent carbon up to the eutectic at 4.3 per cent carbon are known as *hypoeutectic* irons and those from 4.3 per cent carbon upward are called *hypereutectic.*

105. Constitution of Iron. The constitution of iron is shown at the left side of Fig. 41. Ingot iron which contains small amounts of impurities (Art. 114) is a commercial iron that is typical of this class. Iron completely free from impurities has never been obtained. However, the constitution of iron of zero per cent carbon, as shown in Fig. 41, has been obtained experimentally from iron containing extremely small amounts of impurities.

When pure iron is cooled from the liquid state, a temperature effect is noticed at 1535° C. (2795° F.) (the melting point of iron), a second at 1400° C. (2555° F.), a third at 910° C. (1670° F.), and a fourth at 770° C. (1420° F.). The last three temperature effects correspond to retardations in the cooling curve which are due to allotropic changes in the metal. Such allotropic changes are due to rearrangement of the atoms in the solidified metal and are accompanied by evolution of heat. The four allotropic forms of pure iron are in order: delta, gamma, beta, and alpha iron. Delta iron is not of much practical importance since, as the diagram indicates, it is stable only above the top forging temperature. Gamma iron has a face-centered cubic space lattice, is paramagnetic, and is stable above 910° C. (1670° F.) in the range of forging and hot-working. Much doubt has been expressed as to the existence of beta iron (below 910° C. [1670° F.] and above 770° C. [1420° F.]), especially since the methods of X-ray examination of metals have been so greatly improved. From the viewpoint of the engineer it makes little difference whether beta iron exists or not, as the valuable properties of steel are associated with the alpha and gamma forms. Beta iron has a body-centered cubic space lattice. Alpha iron forms below 770° C. (1420° F.), has a body-centered cubic arrangement, and is ferromagnetic.

On heating iron from a low temperature, the heat effects take place in the reverse direction at very closely the same temperatures as for cooling if the heating and cooling operations are carried on very slowly; for ordinary rates of temperature change, the heat effects take place on heating at slightly higher temperatures than on cooling.

As these changes were first studied in detail by the French metallurgist, Osmond, the names and abbreviations corresponding to the temperature effects have been taken from the French. The symbols used are A (*arrêt*) meaning stop, c (*chauffage*) referring to a temperature rise, and r (*refroidissement*) applied to the falling temperature. For example, Ar_3 indicates the change at about 910° C., when iron is cooled, and Ac_1 is applied to the heat evolution occurring at a temperature of about 723° C. when iron is heated. These points are referred to as the *critical points* in iron. Since the Ac and Ar points are very close for very slow rates of

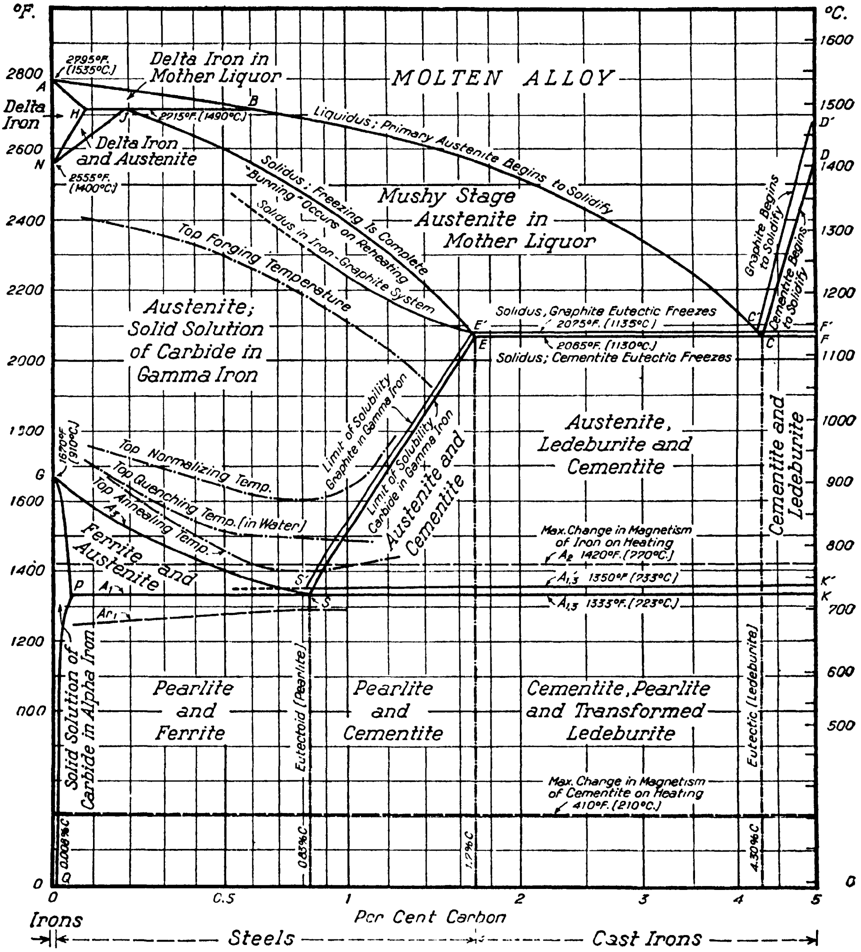

FIG. 41.—Equilibrium Diagram for Iron-carbon Alloys. (Courtesy of American Society for Metals.)

heating and cooling, the letter *A* without either symbol *c* or *r* is used in Fig. 41 to denote the average temperature.

A change in magnetism of iron on heating occurs at Ac_2 (770° C.), where alpha iron which is ferromagnetic is transformed into beta iron which is paramagnetic, possessing only slight magnetic effects.

106. Constitution of Steel. Steel is essentially an alloy of iron and carbon, although various other elements are usually present. In the "plain carbon" steels, sulfur, phosphorus, manganese, and silicon are present in small amounts while chromium, nickel, or other elements are found in the alloy steels.

A comparison of the iron-carbon equilibrium diagram with those previously considered in Chapter III shows it to be a combination of various simple types. The area *ABJHN* dealing with transformations of delta iron will not be considered in this volume since these are not of primary importance for engineers.

FIG. 42.—Pearlite 250×. (Homerberg.)

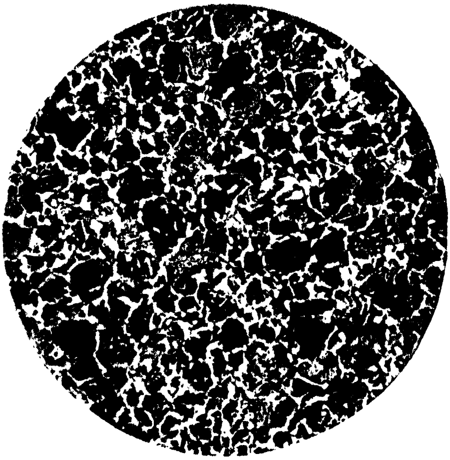

FIG. 43.—Microstructure of Slowly Cooled 0.4% Carbon Steel 250×. (Homerberg.)

Molton alloy when cooled to the liquidus line *BC* begins to solidify as austenite, which is the solid solution of carbide in gamma iron. Carbon is soluble in austenite up to 1.7 per cent. Molten alloys containing up to 1.7 per cent carbon solidify along the solidus line *JE* into austenite. Molten alloys containing from 1.7 to 4.3 per cent carbon solidify as austenite and a eutectic mixture, called ledeburite, composed of saturated austenite and cementite. Molten alloys containing 4.3 per cent carbon solidify as ledeburite, while those containing more than 4.3 per cent carbon solidify along the line *DC* to form cementite, until *CF* is reached, when ledeburite is formed. The constitution of those alloys containing more than 1.7 per cent carbon is discussed further in Chapter VIII, "Cast Iron."

Further slow cooling of austenite for those alloys classed as steels (below 1.7 per cent carbon) causes transformation from the solid-solution state into the eutectoid state. Austenite containing exactly 0.83 per cent carbon will be transformed into the eutectoid at *S* (Fig. 41). The eutectoid *S* is an intimate mixture of pure iron (called *ferrite*) and iron carbide (*cementite*) which, because of its resemblance to mother of pearl under certain forms of lighting, has been called the pearly constituent, or *pearlite.* Pearlite has the characteristic laminated or thumbprint structure shown in Fig. 42.

When austenite containing 0.15 per cent carbon is slowly cooled, pure iron (called ferrite) separates along the line *GS*, the remaining solid solution becoming increasingly richer in carbon until it contains 0.83 per cent carbon and so corresponds to the eutectoid *S*, which then forms. The iron has changed from gamma iron through beta iron and into alpha iron. The resulting structure is a mixture of ferrite crystals with pearlite crystals and is typical of hypoeutectoid steels (Fig. 43).

When austenite containing 1.6 per cent carbon is slowly cooled, separation occurs along the line *ES*. The austenite then decomposes into *cementite*, and the remaining austenite becomes poorer in carbon as the cooling proceeds until it contains only 0.83 per cent carbon at *S*, where the eutectoid is formed. The resulting hypereutectoid structure consists of a mixture of cementite and pearlite (Fig. 44).

Consideration of the diagram indicates, then, that, if a steel is cooled so slowly that all changes have taken place, only three combinations of constitutents are possible: (1) in the hypoeutectoid steels (below 0.83 per cent carbon), ferrite and pearlite will be found in varying amounts; (2) at 0.83 per cent carbon the eutectoid pearlite occurs alone; and (3) in the hypereutectoid steels (above 0.83 per cent carbon), cementite and pearlite will be found. The relative amounts of the three constituents are shown graphically in Fig. 45.

Fig. 44.—Microstructure of Slowly Cooled 1.6% Carbon Steel 250×. (Homerberg.)

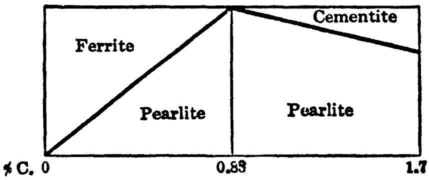

Fig. 45.—Constitution Diagram for Slowly Cooled Steels.

The physical properties of the three constituents are approximately as follows:

Ferrite is soft and ductile.
  Tensile strength, 40,000 pounds per square inch.
  Elongation, 40 per cent in 2 inches.
Pearlite is harder and less ductile.
  Tensile strength, 125,000 pounds per square inch.
  Elongation, 15 per cent in 2 inches.
Cementite is hard and brittle. Its tensile strength is not known because it has been obtained only in fine crystals.

Pearlite is characteristic only of slowly cooled, fully annealed steel. If the mechanical properties of the micro-constituents are known, it is possible to estimate with a fair degree of accuracy the properties of any slowly cooled steel by a calculation of its microstructure from its chemical composition. This can be done most readily by means of Fig. 45.

If the three constituents, ferrite, cementite, and pearlite, were the only possible ones, steel would be limited in its properties. It is known that many changes in the physical properties can be produced by the operations of quenching, tempering or drawing, annealing, and similar forms of heating and cooling classified under the general name of "heat treatment."

107. Hardening or Quenching. Whenever a solid solution decomposes with falling temperature into the eutectoid, this decomposition may be more or less complete depending on the cooling rate. The hardening of steel is an illustration of this phenomenon. If the steel is cooled slowly from above *GSE* (Fig. 41), the changes just considered will take place. If, however, the steel is cooled as quickly as possible, decomposition into the eutectoid will be prevented and the carbon will be retained more or less completely in the solid solution. If the cooling could be carried out with extreme speed the perfect solid solution of carbon in gamma iron, austenite, would be formed. Austenite has a face-centered space lattice, is soft and ductile, and has considerable strength. It is non-magnetic. Ordinary carbon steel cannot be cooled quickly enough to produce austenite at normal temperature, but it may be produced in alloy steels such as nickel and manganese steel. In actual practice the most rapid cooling produces only a partial change in carbon steel, leading to the next decomposition product, *martensite*.

Martensite is the usual product of water-quenching. It is considered by some authorities to be a solid solution of carbon in alpha iron with a body-centered space lattice. Martensite is magnetic and has an interlacing needle-like structure. It is an extremely hard substance but is wholly lacking in ductility. Martensite is not as hard as cementite, however.

Files and the faces of drop-forging dies sometimes show martensitic structure. Martensite differs from pearlite and cementite in that it is not a substance of definite chemical composition but varies in properties with the carbon of the steel. There is, for example, low-carbon martensite at one end and excessively hard and brittle high-carbon martensite at the other. Ferrite and martensite will be found in steel quenched below Ar_3 but above Ar_1, while cementite and martensite occur in steel quenched below SE but above Ar_1.

If the steel is cooled somewhat less rapidly than would naturally lead to the formation of martensite, as, for example, if it is cooled in heavy oil, the next decomposition product, *troostite,* is formed (Fig. 46). It is distinguished by its dark color after etching. Troostite is somewhat softer and more ductile than martensite but is a very hard material. It occurs in many tool steels.

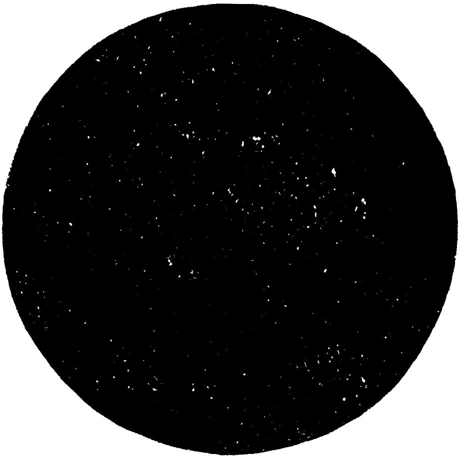

FIG. 46.—Troostite 250×. (Homerberg.)

A still slower cooling rate, as, for example, cooling in air, produces *sorbite,* which is a finely divided mixture of the constituents of troostite and pearlite. It etches to a uniform dark-colored mass with a fine granular structure. Sorbite is one of the toughest forms of carbon steel and is much used in the construction of rails, bridges, guns, shafting, and parts subjected to severe shock.

Like martensite, these other intermediate forms are not of definite chemical composition but vary in mechanical properties with the carbon content of the steel. The amount of hardening depends upon the percentage of carbon in the steel. Ferrite is scarcely hardened at all by sudden cooling. It is the carbon in the solid solution that makes possible the transformations into different decomposition products. Low-carbon steels cannot be hardened by quenching to the same extent as high-carbon steels.

The series of changes, from martensite to troostite to sorbite to pearlite, causes a gradual decrease in tensile strength with a corresponding increase in ductility. The order of magnitude of these changes is indicated in the following table stating the approximate mechanical properties of a steel containing 0.4 per cent carbon.

Constituent	Tensile Strength, lb. per sq. in.	Elongation, per cent in 2 in.
Martensite	200,000	0
Troostite	160,000	4
Sorbite	125,000	10
Pearlite and ferrite	80,000	15

These figures must be taken as suggestive only, as they naturally vary with the carbon content of the steel and with the exact method of cooling.

All hardened steel is in a state of strain, and steel pieces with sharp angles or grooves sometimes crack immediately after hardening. For this reason tempering must follow the quenching operation as soon as possible. Quenching strains due to water-hardening are always more severe than those caused by oil-hardening, and alloy steels with very few exceptions are oil-hardened.

Successful hardening of steel is an art which requires much experience, but a few general principles apply.

(1) Steel should always be annealed before hardening, to remove forging or cooling strains.

(2) Heating for hardening should be slow.

(3) Steel should be quenched on a rising and not on a falling temperature. The reason for this suggestion is that, as the temperature of heating increases above the Ac_3 line, the grains tend to increase greatly in size with a corresponding decrease in the physical properties of the material.

Many quenching mediums have been proposed, but practically any desired degree of hardness can be produced by means of one of the following: (1) brine for maximum hardness, (2) water for the rapid cooling of the common steels, and (3) light, medium, or heavy oil for use with common steel parts of irregular shape or for alloy steels. The rate of cooling, and therefore the hardness of the steel, decrease with the increasing density of the quenching oil.

108. Tempering of Steel. The changes just considered, which are associated with variations in the cooling rate, are hard to control because of the difficulty of regulating the cooling rate. The changes that the solid solution undergoes with variation in the rate of cooling may be duplicated, however, and much more accurately controlled by reheating the martensite which has been formed by quenching. This operation is called *tempering,* which may be defined as the process of reheating a hardened steel to a definite temperature below the critical temperature, holding it at that point for a time, and cooling usually by quenching for the purpose of obtaining toughness and ductility in the steel. This operation is commonly called "drawing" if carried out below 400° C. (752° F.), and "toughening" if temperatures higher than 400° C. are used. The changes in structure obtained by tempering hardened steel are shown by Fig. 47.

Austenitic steel is not produced by ordinary commercial methods of hardening except in the case of certain alloy steels like manganese steel. Under most carefully controlled conditions, a carbon steel which is partially austenitic may, however, be derived. Austenite undergoes transformation to martensite as soon as heating is begun, and martensite alone exists when a temperature of 200° C. (392° F.) is reached. Usually, however, martensite is a common constituent of commercially hardened steel. The martensite begins to be transformed to troostite at 200° C. (392° F.), which alone remains when a temperature of 400° C. (752° F.) is reached. Further heating above 400° C. (752° F.) causes the gradual conversion of troostite into sorbite, which alone exists above 600° C. (1112° F.). If the heating were continued past the critical temperature, only austenite could exist.

When troostitic steel is tempered, no change is effected unless heating is carried beyond 400° C. (752° F.), when the changes above noted for other steels again take place. If wholly troostitic steels were encountered in practice, no tempering would be required; but since some martensite is usually present in even the most distinctly troostitic steel, tempering is required. The change which takes place is the gradual transformation of the martensite to troostite, no martensite being present above 400° C. (752° F.).

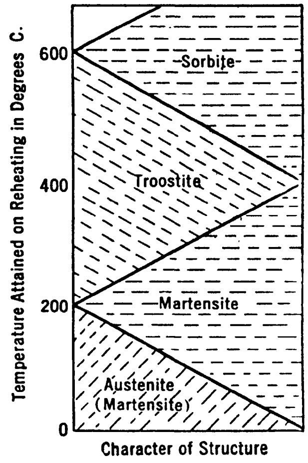

Fig. 47.—Structures Obtained in Tempering Steel.

Troosto-sorbitic steels are a rare possibility among commercially hardened steels. The degree of hardening is so slight and the constituents so stable that tempering does not produce any effect unless carried above 400° C. (752° F.), when the troostite is gradually converted into sorbite.

Two considerations which affect the practice of tempering steels follow. First, the transformation of one constituent to the succeeding form is dependent not solely upon the temperature attained, but also upon the relative rapidity or slowness with which the temperature is reached, and upon the time allowed at this temperature. Slow heating, or holding at a given temperature for a measurable interval, will produce a greater degree of tempering than would otherwise be effected at a given temperature. Second, when, as often happens in practice, the reheating of the hardened steel is done in such a manner that, if not arrested quickly, the temperature would continue to rise after the desired tempering heat is reached, it is necessary to cool the metal quickly by immersion in some quenching medium. This explains the reason for the common tempering practice of quenching from a rising temperature in order to stop the tempering action so as to get a definite hardness. If the temperature does not rise after the desired tempering effect is reached, it is immaterial whether quenching follows or not, since the rate of cooling after the temperature is reached is secondary in importance. Slow cooling from the tempering temperature is frequently employed instead of the usual quenching.

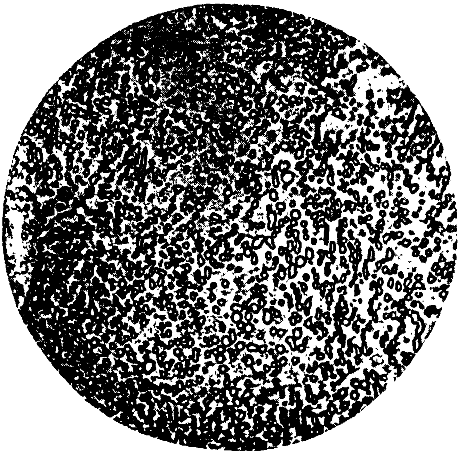

FIG. 48.—Spheroidized Cementite 500×. (Zavarine.)

Tempering may be effected by heating the hardened steel in a forge, but it is more carefully controlled if the reheating is done by means of salt baths, melted lead, or the electric oven.

Sorbite is formed by heating hardened steel in the range from 400° C. (752° F.) up to the Ac_1 and is characteristic of toughened steel. This constituent has a silver-gray luster and shows a finely emulsified ferrite-cementite structure. It is, in fact, imperfectly formed pearlite, from which it differs in that it is less ductile but has a greater tensile strength and a much higher elastic limit. An increase in toughening temperature lowers the tensile strength and elastic limit but increases the ductility and dynamic strength. The maximum resistance to shock is obtained by heating to about 40 degrees below the Ac_1.

Pearlite cannot be formed by reheating hardened steel. That temperature which might be expected to produce pearlite forms instead a structure known as "spheroidized cementite" (Fig. 48). Steel in this condition has excellent machining qualities. This is the condition sought in properly annealed tool steel.

109. Annealing. *Annealing* is the process of heating a metal above the critical temperature range, holding at that temperature for a proper period of time, and then slowly cooling. The metal is ordinarily allowed to cool slowly in the furnace. The three chief functions of annealing are: (1) to soften the steel to meet definite specifications or to make machining easier; (2) to relieve internal strains caused by quenching, forging, cold-working or in other ways; and (3) to refine the grain.

The piece should be heated slowly enough to permit uniform diffusion of heat. When the steel reaches the Ac_1 temperature on reheating, pearlite begins to dissolve with the formation of austenite. At Ac_3 the solution of the ferrite is complete and only exceedingly fine-grained austenite is left. This, often referred to as the "rebirth" temperature, corresponds to the maximum refinement of the grain. If heating is continued above Ac_3 the grains increase in size, giving less satisfactory material. The particular treatment is varied, depending upon the percentages of carbon and impurities in the steel, the size of the piece, and the physical properties desired. Hypoeutectoid steels should ordinarily be heated from 25° C. to 50° C. above the Ac_1 line. The annealing temperatures commonly used are:

Range of Carbon Content, per cent	Range of Annealing Temperature
Less than 0.12	875 to 925° C. (1607 to 1697° F.)
0.12 to 0.29	840 to 870° C. (1544 to 1598° F.)
0.30 to 0.49	815 to 840° C. (1499 to 1544° F.)
0.50 to 1.00	790 to 815° C. (1454 to 1499° F.)

The two exceptions to the general rule are very low-carbon steel, which should be annealed below 550° C. (1022° F.), and high-speed steel, which is annealed at a temperature of incipient fusion.

Process annealing is commonly applied on sheets and wires by heating to a temperature below or close to the lower limit of the critical range (usually from 550° C. to 650° C.) followed by slow cooling.

Another operation which is very similar to annealing is called *normalizing*. This may be defined as heating above the upper critical range and cooling to below that range in still air at ordinary temperature. Normalizing is employed to obtain uniform conditions in metals previously treated in different ways and is often applied to alloy steels and machined parts, especially if they are later to be heat treated.

110. Example of Heat Treatment. The heat treatment of a 0.40 per cent carbon steel is given as an example. This is a medium-high-carbon steel of fair machining properties and good hardening characteristics, suitable for small and medium-sized forgings. The forging would be normalized or annealed at a temperature of 815 to 840° C. (1499 to 1544° F.) to give a structure of suitable machining properties (Fig. 41). After machining it would be hardened by heating to 830 to 860° C. (1526 to 1580° F.) and quenching in water or oil, depending upon the section. The hardened piece (martensitic structure) is then tempered to desired hardness or structure. Refer to Fig. 47. Thus, if a sorbitic structure is desired, the steel would be reheated to 600° C. (1112° F.), held at that temperature for a time, and then quenched.

111. Grain Size Control. Grain size control of steel is an important factor in heat treatment, forging, case-hardening, and mechanical working. A test for determination of grain size was originated by McQuaid and Ehn. The American Society for Testing Materials has a standard method of test for grain size. Steel of a given grain size is specified for many applications in order to give greater latitude for safe heat treatment and mechanical operations.

It is well established that grain size affects the physical properties of steels. For example, of two mild steels of the same composition and tensile strength, one may have a low impact value due to coarseness of grain. By subjecting this steel to a normalizing treatment at 900° C. (1652° F.), the grain can be refined and the full impact value obtained. However, it is desirable to be able to obtain proper fine grain size consistently after the usual heat treatment and mechanical working. This can be accomplished by specifying suitable fine grain size so that the size of grain will be unchanged by any of the heat-treating operations except uncontrolled over-heating. An ordinary steel of coarse grain size may have grain growth beginning at about 730° C. (1346° F.), which is within the range of everyday operations, but a controlled fine-grained steel will not begin to grow until 1000° C. (1832° F.) is reached, which is above the temperature of most operations except those for high-speed tool steel and high-alloy steels.

Forgings of greater strength and density can be formed from coarse-grain-size steel on account of its tendency to produce sounder metal and more uniformly flowing metal than fine-grain-size steel.

Shearing is an important operation in flash trimmings of forgings or stamping for automobile connecting rods, front axles, etc. Steel of fine grain size is tougher and offers greater resistance to shearing but shows less tendency to crack at the edges. Since any fine cracks develop on subsequent heat treatment, the selection of suitable fine-grain-size steel is important in decreasing cracking.

112. Case-hardening. An operation closely allied to the heat treatment of steel is that known as case-hardening or case-carburizing. Case-hardening is a form of cementation applied to low- or medium-carbon steels in order to impregnate them with carbon to a depth of a few hundredths to one-fourth of an inch, thus securing a high-carbon case which may subsequently be hardened by quenching. The advantage gained by this treatment is that a surface is produced which will withstand wear, abrasion, cutting, or indentation, and at the same time the core is left soft and tough so that the shock resistance of the material is not impaired. Case-hardening is especially applicable to the construction of armor-plate, safes and vaults, the moving parts of machinery which are subjected to both shock and wear, such as crankshafts, pivots and axles, and gears, also for the bearings and knife-edges of weighing machinery, and for many other purposes in machine and implement construction. For many of the purposes above listed, certain of the alloy steels which combine great hardness with great toughness are now often preferred.

Usually, the steel for case-hardening is one originally containing from 0.1 to 0.2 per cent carbon, and the operation is generally applied to the finished casting, forging, or otherwise fabricated object, so that no machine work need be done on the hardened surface.

Steel for case-hardening should have an intermediate grain size for ordinary practice. With coarse-grained steel, quicker, deeper, and more even penetration of carbon is obtained, producing a harder and more even case, but the coarseness is limited by the greater tendency to crack, warp, and check on grinding. Fine-grained steel causes more shallow hardening but freedom from the above defects.

The general method of case-hardening consists in heating the steel in contact with carbonaceous matter such as potassium ferrocyanide, charcoal, barium carbonate, bone dust, or charred leather. The usual temperature of heating is about 900° C. (1652° F.). A more rapid penetration of the carbon may be secured by means of higher temperatures, but this practice is attended by the danger of the growth of coarse grains in the interior at the temperature of carbonization, resulting in loss of toughness and strength unless the steel is subsequently reheated to restore the grain size. Enfoliation, which is the splitting off of case from the core, may also occur at high temperatures. Furthermore, more heat units are required and furnaces deteriorate more rapidly at high temperatures. A time of 2 to 12 or more hours is required for the process, depending upon the temperature of the furnace and the class of carburizer. Many special or alloy steels are often treated by a case-hardening process with very beneficial results. Nickel and chrome steels are especially valuable for case-hardening.

Because of the duplex character of case-hardened steel (the core has about 0.2 per cent carbon while the case has 0.83 per cent or more) a double heat treatment is common. The material is:

(1) Annealed at Ac_3 to refine the grain of the core, and
(2) Annealed at Ac_1 and quenched to refine the grain of the case, and
(3) Tempered to meet the conditions required.

A method of surface hardening known as "nitriding," is discussed under "Alloy Steels" (Art. 257).

STEEL CASTINGS

113. Steel Castings. Steel castings are made by pouring molten steel into sand molds in a manner similar to that employed for iron castings (Chapter VIII). Steel products of intricate shape can usually be manufactured more cheaply by casting than by rolling or forging processes, especially in small quantities. Steel castings are tougher and stronger than castings of gray iron or malleable iron.

Foundry Practice. Steel for castings may be produced in steel foundries by means of the Bessemer, open-hearth, crucible, electric-furnace, or duplex processes. The equipment is ordinarily of relatively small size as compared with that in steel mills.

Molds for steel castings are similar to those for iron castings. Both green-sand and dry-sand molds are used for steel castings. (See Art. 160.) The molding sands should have a high fusion point since steel is cast at a higher temperature than cast iron. The shrinkage of ordinary carbon steel is about ¼ inch per foot.

Defects. Defects which often occur in steel castings are blowholes, shrinkage cavities, ingotism, segregation, and cracks formed by contraction of the steel in the solid state.

Specifications. The American Society for Testing Materials has specifications for four grades of steel castings for railroads.* Grade B castings are specified for truck side frames, bolsters, and locomotive frames and wheel centers. These castings must be annealed. The maximum percentage composition for Grade B castings is specified as follows: manganese, 0.85; phosphorus, 0.05; sulfur, acid process, 0.06, basic process, 0.05. The percentages of carbon and silicon are to be selected by the manufacturer to obtain the following minimum physical properties (for Grade B castings): tensile strength and yield point, 70,000 and 38,000 pounds per square inch, respectively; elongation, 24 per cent in 2 inches; and reduction of area, 36 per cent. The carbon content for carbon-steel castings does not ordinarily exceed 0.6 per cent. The physical tests are conducted on specimens machined from test coupons which are cast attached to the main casting such as a locomotive frame and are annealed with the casting.

Uses. Typical uses of steel castings are locomotive castings and frames, draw-bars for railroad cars, machinery and automotive castings, and manganese-steel castings for railroad rail frogs and crossings and for wearing parts of crushing machinery.

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* *A.S.T.M. Book of Standards*, 1936, A 87-36, p. 247.

INGOT IRON

114. Ingot Iron. Ingot iron is a commercially pure iron. It has a very low percentage of impurities, the total content of carbon, silicon, manganese, phosphorus, and sulfur usually being less than 0.08 per cent. From a practical standpoint it can be classified as ferrite. The chief characteristic of ingot iron is its resistance to corrosion as compared with low-carbon steel.

Manufacture. Ingot iron is manufactured by the basic open-hearth process. Production of an iron low in impurities requires careful selection of raw materials, an additional period of time in the furnace for purification, and careful control of the operation. The process is more expensive than for steel because of extra fuel needed to maintain longer heats and the high-grade refractories need for the furnace lining in order to withstand the longer heating and the corrosive action of the slag which is high in iron oxide. Pouring into ingots and rolling into shapes require special care to secure sound metal. Ingot iron is readily galvanized and corrugated.

Tensile Properties. Ingot iron has a tensile strength of about 40,000 pounds per square inch, a yield point of about 25,000 pounds per square inch, a minimum elongation in 8 inches of 22 per cent for ½-inch plate, and a reduction of area of at least 65 per cent. Brinell hardness varies from 80 to 100.

Uses. Ingot iron is used extensively for culverts, gutters, eaves troughs, fencing, wire, furnace metal, and galvanized sheet metal of various types.

THE PHYSICAL PROPERTIES OF STEELS

115. Grades of Steel and General Properties. The following grades or classes of steels are among those most commonly recognized, their approximate tensile properties when in the annealed condition being as indicated in Table II.

The modulus of elasticity of all grades is about 29,000,000 pounds per square inch.

The principal factors influencing the strength, ductility, and elastic properties of steel are: (1) the carbon content; (2) the percentage of silicon, sulfur, phosphorus, manganese, and other alloying elements; and (3) the heat treatment and mechanical working. The factors are not necessarily independent, and their effects are usually combined. The nature and extent of the effect of heat treatment and mechanical working are inevitably dependent upon the amounts of carbon and other elements present.

TABLE II

GRADES OF STEEL

Class by Uses	Class by Manufacture, etc.	Per Cent C	Elastic Limit, lb. per sq. in.	Tensile Strength, lb. per sq. in.	Per Cent Elongation in 8 in.
Boiler rivet......	Dead soft open-hearth	0.08–0.15	25,000	50,000	30
Structural rivet...	Soft O. H............	0.15–0.22	30,000	55,000	30
Boiler plate......	Soft Bessemer or O. H.	0.08–0.10	30,000	60,000	25
Structural steel...	Medium O. H........	0.18–0.30	35,000	65,000	25
Machinery steel..	Hard O. H...........	0.35–0.60	40,000	75,000	20
Rail steel........	Hard Bess. or O. H ...	0.35–0.55	40,000	75,000	15
Spring steel......	High-carbon O. H	1.00–1.50	60,000	125,000	10
Tool steel	High-carbon O. H. or crucible............	0.90–1.50	80,000	150,000	5

116. Effect of Carbon upon Physical Properties. The distinctive properties of the different grades of plain carbon steel are due to variations in carbon content more than to any other single factor. Carbon always acts as a hardener and strengthener, but at the same time reduces the ductility.

The effect of carbon upon the tensile properties of carbon steels is shown in Table III:

TABLE III

TENSILE PROPERTIES OF CARBON STEELS[1]

Per Cent Carbon	Yield Point, lb. per sq. in.	Ultimate Tensile Strength, lb. per sq. in.
0.09	30,000	52,500
0.20	39,500	68,400
0.31	46,500	80,600
0.37	50,000	85,200
0.57	55,000	117,400
0.81	70,000	149,600
0.97	79,000	152,600

[1] Made at Watertown Arsenal on open-hearth steels.

Many formulas have been suggested for the strength of carbon steels in terms of carbon, phosphorus, sulfur, manganese, etc., but none of them are continuous functions for any great range. An approximate formula often used in estimating the strength of a carbon steel is

$$\text{Tensile strength} = (40{,}000 \text{ to } 45{,}000) + 1000\,C$$

where C is the number of *points of carbon* in the steel, 1 point of carbon being equivalent to 0.01 per cent carbon.

117. Effects of Silicon, Sulfur, Phosphorus, and Manganese. The direct effect of *silicon,* in the ordinary proportions commonly encountered in steels (usually not over 0.2 per cent), upon strength and ductility is very slight. Whatever effect there may be is difficult to determine, because it is masked by the influence of other elements, like carbon and phosphorus, which cannot be made to be altogether constant factors. Increasing the silicon content intentionally to 0.3 or 0.4 per cent has the effect of raising the elastic limit and ultimate strength of the steel considerably, without reducing the ductility greatly. This is sometimes done in the production of steel castings.

Sulfur, within the limits common to ordinary steels (0.02 to 0.10 per cent), has no appreciable effect upon the strength or ductility of steels. It has, however, a very injurious effect upon the properties of the hot metal in lessening its malleability and weldability, thus causing difficulty in rolling, called "red-shortness." If it were possible that the steel might contain an excess of sulfur over that which is neutralized by manganese, the effect would certainly be to reduce both strength and ductility. Specifications for structural steels commonly limit the sulfur content to a maximum of 0.04 to 0.05 per cent.

Phosphorus is the most undesirable of all the elements commonly found in steels. Its effect upon the properties of steels is very capricious, but it is always detrimental to toughness or shock resistance, and often detrimental to ductility under static load. Campbell states that the strength of steel under static load is increased by 1000 pounds per square inch for each 0.01 per cent of phosphorus so long as the total phosphorus does not exceed 0.12 per cent. Beyond this limit even static strength is diminished. High-phosphorus steels are apt to break under very slight stress if this stress is suddenly applied or if vibration is encountered, and this fact alone is sufficient to bar such steels from most uses in construction. Specifications commonly limit the phosphorus content of structural steels to a maximum of 0.04 to 0.06 per cent.

Manganese is an element which is commonly comparatively high in most steels because of the prevalent practice of using either spiegeleisen or ferromanganese as a recarburizer and deoxidizer in the Bessemer and open-hearth processes. The effect of manganese upon the properties of steel is a rather involved question, but it has a tendency to increase the strength, provided that a certain limit is not exceeded. If this limit is exceeded its effect in the direction of increasing brittleness causes a reversal of its effect upon strength. With less than 0.3 or 0.4 per cent manganese the steel is likely to be impregnated with oxides the harmful effect of which outweighs any beneficial effect due to the manganese. Between

0.3 and 0.4 per cent and about 1.5 per cent manganese, the beneficial effect is dependent upon the amount of carbon present. With 0.1 per cent of carbon (according to Bradley Stoughton), the strength is increased about 100 pounds per square inch for each 0.01 per cent of manganese over 0.3 or 0.4 per cent; with 0.2 per cent carbon, the gain is about 165 pounds per square inch for each 0.01 per cent of manganese; and with 0.4 per cent of carbon the gain is about 280 pounds per square inch for each 0.01 per cent of manganese. The beneficial effect is always somewhat more marked with acid than with basic steel. As the content of manganese rises above 1.5 or 2.0 per cent the metal becomes so brittle as to be worthless, but as the content of manganese is further increased to about 6 or 7 per cent a curious reversal takes place.

118. Effects of Heat Treatment upon Physical Properties. The effects of different heat treatments upon the mechanical properties of carbon steels of various compositions are shown in Table IV.

TABLE IV

MECHANICAL PROPERTIES OF HEAT-TREATED CARBON STEELS.[1]

Composition		Heat Treatment	Yield Point, lb. per sq. in.	Tensile Strength, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Brinell Hardness
Carbon, per cent	Manganese, per cent						
0.14	0.45	Hot-rolled	45,000	59,500	37.5	67.0	112
		Annealed	31,000	54,500	39.5	67.0	107
		Quenched in water	......	90,000	21.0	67.0	170
		Quenched in oil	56,500	71,500	34.0	75.5	134
0.32	0.51	Hot-rolled	49,500	75,500	30.0	51.9	144
		Annealed	41,000	70,000	30.5	51.9	131
		Quenched in water	......	135,000	8.0	16.9	255
		Quenched in oil	67,500	101,000	23.5	62.3	207
		Quenched in oil: tempered at 650° F	61,500	84,000	30.0	71.4	163
0.46	0.40	Hot-rolled	52,500	86,500	22.5	30.7	160
		Annealed	48,000	79,500	28.5	46.2	153
		Quenched in water	..	220,000	1.0	0.0	600
		Quenched in oil	87,500	126,500	20.5	51.9	255
		Quenched in oil: tempered at 560° F	81,500	111,500	24.0	57.2	...
		Quenched in oil: tempered at 650° F	73,000	98,000	25.5	59.8	192
0.57	0.65	Hot-rolled	57,000	106,500	19.0	27.4	220
		Annealed	50,000	95,000	25.0	40.3	183
		Quenched in water	..	215,000	0.0	0.0	578
		Quenched in oil	105,000	152,000	16.5	40.3	311
		Quenched in oil: tempered at 460° F	97,500	145,000	16.0	46.2	293
		Quenched in oil: tempered at 650° F	79,500	113,000	24.0	62.3	228
0.71	0.67	Hot-rolled	66,000	128,000	15.0	20.5	240
		Annealed	46,500	111,500	16.5	24.0	217
		Quenched in oil	100,000	184,500	1.5	0.0	364
		Quenched in oil: tempered at 460° F	115,500	177,000	10.0	34.0	340
		Quenched in oil: tempered at 560° F	106,000	148,500	17.0	43.0	311
		Quenched in oil: tempered at 650° F	91,000	125,500	19.5	57.2	269

[1] Data from American Society for Steel Treating.

119. Tensile Properties. The tensile properties of various carbon steels called for in the standard specifications of the American Society for Testing Materials are summarized in Table V.

TABLE V

TENSILE PROPERTIES OF VARIOUS STEELS

Kind and Use of Steel			Tensile Strength, lb. per sq. in.	Yield Point, min. lb. per sq. in.	Elongation, min. in 8 in. per cent	Elongation, min. in 2 in. per cent	Reduction of Area, min. per cent
Structural steel for bridges	Structural		55–65000	30000, or 0.5 (u.t.s.)[1]	$\frac{1500000}{\text{u.t.s.}}$	22	
	Rivet		46–56000	25000, or 0.5 (u.t.s.)	$\frac{1500000}{\text{u.t.s.}}$		
Structural steel for buildings	Structural		55–65000	30000, or 0.5 (u.t.s.)	$\frac{1400000}{\text{u.t.s.}}$	22	
	Rivet		46–56000	25000, or 0.5 (u.t.s.)	$\frac{1400000}{\text{u.t.s.}}$		
Structural steel for ships	Structural		58–68000	0.5 (u.t.s.)	$\frac{1500000}{\text{u.t.s.}}$		
	Rivet		55–65000	0.5 (u.t.s.)	$\frac{1500000}{\text{u.t.s.}}$		
Splice bars	Extra high-carbon		100000	......	......	10	
	High-carbon		85000	......	......	14	
	Medium-carbon		68000	......	......	$\frac{1600000}{\text{u.t.s.}}$	
	Low-carbon		55–65000	......	......	25	
Cold-rolled steel axles			70000	60000[2]	......	18	35
Steel castings (class A)	Hard		80000	0.45 (u.t.s.)	......	17	25
	Medium		70000	0.45 (u.t.s.)	....	20	30
	Soft		60000	0.45 (u.t.s.)	....	24	35
Boiler and firebox steel	Flange		55–65000	0.5 (u.t.s.)	$\frac{1500000}{\text{u.t.s.}}$		
	Firebox		55–65000	0.5 (u.t.s.)	$\frac{1550000}{\text{u.t.s.}}$		
Boiler rivet steel			45–55000	0.5 (u.t.s.)	$\frac{1500000}{\text{u.t.s.}}$		
Billet steel concrete reinforcing bars	Plain bars	Structural grade	55–70000	33000	$\frac{1400000}{\text{u.t.s.}}$		
		Intermediate grade	70–90000	40000	$\frac{1300000}{\text{u.t.s.}}$		
		Hard grade	80000 min.	50000	$\frac{1200000}{\text{u.t.s.}}$		
	Deformed bars	Structural grade	55–70000	33000	$\frac{1250000}{\text{u.t.s.}}$		
		Intermediate grade	70–90000	40000	$\frac{1125000}{\text{u.t.s.}}$		
		Hard grade	80000 min.	50000	$\frac{1000000}{\text{u.t.s.}}$		
Concrete reinforcing bars from rerolled steel rails	Plain bars		80000	50000	$\frac{1200000}{\text{u.t.s.}}$		
	Deformed bars		80000	50000	$\frac{1000000}{\text{u.t.s.}}$		

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[1] u.t.s stands for "ultimate tensile strength."

[2] Elastic limit, not yield point.

Merit Numbers. Comparisons of steel are sometimes made by their so-called *merit numbers,* of which there are various types. The simplest forms are directly proportional to the product of the tensile strength and the per cent elongation as found by testing a standard 2-inch tensile specimen. Another form embodying more completely the tensile properties of the steel is as follows:

$$\text{Merit No.} = \frac{\left(\frac{\text{Y. P.} + \text{T. S.}}{2}\right) D}{100 - (\text{R. A.})}$$

where Y. P. = yield point, T. S. = tensile strength, D = per cent elongation in 2 inches, and R. A. = per cent reduction of area.

120. Torsional Shear. The strength of steel in torsional shear is shown in Table VI. The modulus of elasticity for shear is about two-fifths of the tensile modulus or about 12,000,000 pounds per square inch.

TABLE VI

STRENGTH OF STEEL IN TORSIONAL SHEAR

Class of Steel	Computed Extreme Fiber Stress, lb. per sq. in.	Shearing Modulus of Elasticity, lb. per sq. in.
Mild Bessemer	64,200	11,320,000
Medium Bessemer	68,300	11,570,000
Hard Bessemer	74,000	11,700,000
Cold-rolled	79,900	11,950,000

M. C. Fetzer found the torsional strength of solid bars of carbon steel to be an average of 68 per cent of the true tensile strength, that is, of the strength per square inch not of the original cross-section, but of the reduced cross-section.

121. The Magnetic Properties of Steel. Large quantities of iron and steel are consumed in the construction of electrical machinery, motors, generators, transformers, etc., where the magnetic properties of the material used are of supreme importance.

The magnetic properties and mechanical properties of irons and steels are dependent upon the same factors, i.e., composition, heat treatment, mechanical working, etc. The mechanical properties can, therefore, at least in a measure, be foretold by the results of magnetic testing.

Relation between Magnetic Properties and Chemical Composition. The following conclusions have been arrived at by de Nolly and Veyret as the result of an investigation of the hysteresis and eddy-current losses of dynamo sheet metals of varying chemical composition.

Carbon. "The carbon percentage should be as low as possible and always remain below 0.1 per cent." A 0.15 per cent carbon steel is greatly inferior to one containing 0.10 per cent carbon.

Silicon. "The presence of silicon diminishes the hysteresis losses considerably. The coefficient η changes from 0.0016 for an iron free of silicon to 0.0009 for a metal containing 3.5 per cent silicon." Silicon also increases the resistivity of the steel and therefore reduces eddy-current losses. In a very weak field silicon increases permeability, but with stronger magnetizing force the effect is reversed and permeability is diminished.

Manganese. Manganese appears to be detrimental to magnetic properties if present in amounts exceeding about 0.3 per cent. The data secured bearing upon the effect of manganese are not very conclusive.

Sulfur and Phosphorus. Both sulfur and phosphorus were found to be elements whose presence in amounts exceeding about 0.3 per cent (for both combined) constitutes a distinct injury to magnetic properties.

Relation between Magnetic Properties and Temperature. Investigation of the changes in magnetic properties of steels as the temperature of the specimen under test is raised or lowered has been made in only a few instances, and little detailed information is available. An extensive study was made in the Chemical Laboratory of Messrs. Schneider's Works at Creusot, and the following remarks are based wholly upon this work.

The method of study followed consisted in subjecting steel specimens of various forms to uniformly increasing and decreasing temperatures in an electric furnace, and simultaneously exposing them to a chosen constant magnetizing force. The temperature indications of a thermocouple mounted in the specimen, and the corresponding intensity of induced magnetism, were continuously recorded autographically on a curve.

One of the facts most emphatically shown by the test results was that the form of the curve obtained varies considerably for specimens of different forms. The maximum strength of magnetizing force employed also affected the character of the temperature-inductance curve.

The specimens for the series of tests were 200 millimeters long, 3 millimeters in diameter, and comprised a series of six steels varying in carbon content from 0.06 to 1.20 per cent. The maximum strength of field employed was 20 gausses, and the frequency was 45 cycles per second.

The most pronounced change of magnetic properties occurs when the critical range of temperatures is reached, at which point an almost total loss of magnetism takes place.

Aside from the great change in magnetism which takes place in passing the critical range of temperatures, other changes of lesser magnitude occur at lower temperatures. In the three steels of lowest carbon content, there is a progressive increase in induction up to a temperature of about 200° C. (392° F.) or 250° C. (482° F.).

All the medium- and high-carbon steels exhibit a certain falling off in magnetism in passing through the range just below 200° C. (392° F.), the loss becoming accentuated as the percentage of carbon increases. This behavior appears to be due to the fact that iron carbide loses its magnetism to a very large degree at a temperature in the neighborhood of 200° C. (392° F.). The phenomenon is naturally most marked, therefore, when the total carbon content, and therefore the carbide content, is greatest.

Relation between Magnetic Properties and Physical Properties. The magnetic testing of iron and steel from the standpoint of correlation of magnetic and physical properties is a comparatively new application of the analysis of magnetic effects. Investigations in this respect have been carried on in various instances in determinations of the structure, elastic state, etc., of certain steel products, such as bearings, saws, cutlery, and tools, with encouraging results. This type of analysis is of value in the detection of flaws in bar stock, welds, rails, etc.; and, in the light of recent improvements in apparatus and methods of testing, a more extensive commercial application is anticipated.

Interlamination Resistance Test. The American Society for Testing Materials has developed a test method for measuring interlamination resistance of a structure composed of strips cut from electrical steel. The resistance, measured in the direction perpendicular to the plane of laminations, indicates the comparative effectiveness of various insulating sheet surface oxides or coatings in reducing intersheet loss. The test is desirable in order to insure that resistance between sheets in a laminated core will not permit sufficient induced currents to flow between laminations so as to affect the core losses materially.

Sperry Transverse Fissure Test. Transverse fissures in steel railroad rails can be detected by means of the Sperry transverse fissure test. The detector is mounted on a railroad car which can be run over the track at a low speed. Since transverse fissures obstruct the flow of the current in the rails, the presence of fissures is automatically determined by noting variations in electric current passing through the head of the rail.

WELDING

122. Pressure Welding. There are two general processes of welding: (1) the pressure process and (2) the fusion process. Pressure welding is carried on by heating the edges to be united to a temperature below fusion, cleaning the surfaces by adding flux to remove oxide, and hammering or pressing the surfaces together so that there is diffusion between the space lattices of the metal on each side of the joint. Pressure welding is accomplished also by electric spot welding.

A *spot weld* is made by passing an electric current through a localized area of the parts to be joined in sufficient quantity that the heat generated in these parts will fuse them together. Alternating current, supplied at low voltage by a transformer, passes through conductors and electrodes to the metal pieces to be welded. The electrodes are pressed. against the metal to restrict the flow of current through the metals to be joined and thus localize the heat in a small spot. Spot welding is suitable for joining metals which do not have to transmit heavy stress.

An improved form of spot welding, called "shot welding," provides for mechanical control of the time of application of the current to insure sufficient heat for a satisfactory weld without danger of damaging the metal by overheating. This process has made possible the welding of alloy steels such as 18-8 chromium-nickel stainless steel without precipitation of chromium carbide near the weld zone, which robs the parent metal of some of its chromium, rendering it less resistant to corrosion. The amount of heat applied in a shot weld can be checked by an ammeter with an automatic recording device.

123. Fusion Welding. Fusion welding consists of depositing molten metal at the joint at a temperature sufficiently high to fuse together the deposited metal with that of the edges of the pieces to be joined. Fusion welding is carried on by one of the following methods: (1) the electric-arc method, (2) the gas-flame method, (3) the atomic hydrogen electric-arc method, and (4) the Thermit process.

124. Electric-arc Method. In this method heat is supplied by an electric arc which passes between the joint and an electrode. The electrode may be bare or covered with a flux. Usually the metal to be welded is made the positive terminal and the electrode the negative terminal because the positive pole is the hotter and a more stable arc is formed. Reversed polarity is often used with covered electrodes. Direct current is usually used in welding because of less danger of shock to operators than with alternating current and because overhead welding is easier.

Metal Arc Welding. In metal arc welding the electrode is of metal which is melted by the heat of the arc and deposited at the joint. An intense but concentrated heat is imparted to the base metal.

One end of the electrode is first brought in contact with the base metal and then raised to a position about 1/8 inch above the base metal. Electrons are emitted across the arc, generating sufficient heat to raise the temperature of the base metal to about 2300° C. (4172° F.) and the electrode to about 2000° C. (3632° F.). Metal from the electrode is deposited in small drops into a crater formed in the base metal. The passage of each drop produces a brief short circuit of the arc. Drops from bare electrodes are smaller than from covered electrodes and cause short circuits about 15 per cent of the time as compared with about 4 per cent for covered electrodes.

Metal electrodes are usually about 1/4 inch in diameter and contain less carbon ordinarily than the base metal. The base metal must be of low- or medium-carbon steel. High-carbon steel cannot be used since the welds formed are hard and brittle.

Fluxes may be applied directly or the electrode rods may be coated with material which melts to form a suitable flux. Calcium oxide and titanium oxide are sometimes added to the flux to increase the rate of emission of electrons from the electrode for the purpose of intensifying the heat. Covered electrodes are preferred since oxidation of metalloids is reduced and less nitrogen is absorbed, largely because of the protective action of gases emitted from the coating materials.

Carbon oxides escape as gases, or, if the welding is carried on too fast, the gases are entrapped in the metal, producing porous welds. Silicon and manganese oxides rise to the surface of the weld as slag. Phosphorus and sulfur are not greatly affected. Absorption of nitrogen reduces ductility.

Carbon Arc Welding. The electrode is of carbon or graphite. A large amount of heat is generated across the arc, fusing the base metal. Filler metal is supplied from a welding rod held in the arc. Sometimes no filler metal is used, the base metal being fused together at the joint.

Shielded Arc Welding. The arc is surrounded by a gas, usually hydrogen, to protect the heated metal from oxidation by contact with the air.

Applications. Electric arc welding, generally conducted with a metal electrode, is used for welding structural members of various types, joints in ships' hulls, joints in pipe lines, and for repairing steel and iron castings.

125. Gas-flame Method. In the gas-flame method, welding-rod metal is fused and deposited on the joint by means of a gas flame. Oxyacetylene gas is required for welding steel in order to get a high enough temperature. Oxyhydrogen gas or oxygen with city gas are sometimes used for welding non-ferrous metals which require only low temperatures. Oxyacetylene gas welding is used for joints in light plating, butt joints of pipes, manufacture of fittings, and repair of steel and iron castings. A large amount of heat is expended in gas flame welding, which causes buckling of plates and shapes. For this reason gas welding is not used much for joints in hulls of ships. The oxyacetylene gas torch operated with an excess of oxygen is an effective burning or cutting tool for steel and iron.

126. Atomic Hydrogen Electric-arc Method. This method is a combination of electric-arc and gas welding. An alternating-current arc changes hydrogen gas from the molecular to the atomic form. The reverse process takes place just outside of the arc on the joint, the recombining of the hydrogen atoms into molecules generating intense heat which melts a thin rod of filler metal held in an atmosphere of hydrogen. The deposited weld metal is surrounded by hydrogen gas which protects it from oxidation. Welds of good quality can be produced by this method.

127. Thermit Method. The Thermit process consists of producing an extremely hot molten steel by ignition of iron oxide in contact with aluminum in a crucible. The reaction gives very hot steel and Al_2O_3 as slag. The hot steel is poured into a mold placed about the joint, producing a solid casting at the joint. Thermit welding is used for joining of trolley rails and repair of large broken parts such as stern posts of ships and side frames of locomotives.

128. Inspection and Testing of Welds. It is important to inspect and test welds for the purpose of detecting defects that might impair the serviceability of welded structures. Inspection of the work while in progress is desirable. In order to determine quality of welding, it is common practice to require operators to make up weld samples that can be subjected to destructive tests. Many times it is difficult to discover faulty work in the interior of welds when only non-destructive tests can be employed.

Common tests of welds of the destructive type are the bending, the nick-break, and the tension tests. The fatigue, the impact, and the compression and drift tests are also sometimes conducted. Non-destructive tests for locating defects in the interior parts of welds have the advantage of not destroying the weld. Specific gravity of some welds can be obtained to locate cavities and inclusions of iron oxide. Pure iron has a specific gravity of 7.85, iron oxide of about 6.0. A specific gravity of 7.8 is required for welds. Cavities and cracks can be detected by noting with a stethoscope the sound of metal when struck with a hammer. The X-ray test has been successful in locating defects, but the weld may have to be cut into samples to get X-ray penetration. The Sperry electrical test is also successfully employed. (See Art. 121.) A hydrostatic internal pressure test for pipes is used for testing welded pipes. Hardness tests can be performed on the surface of welded joints without injuring them.

129. Comparison of Welding with Riveting. The following advantages of welding as compared with riveting may be stated:

1. Greater continuity of strength and greater stiffness are obtained.
2. Welded structures are lighter, since riveted connections require wide laps and gusset plates.

3. Joints have improved tightness.

4. Structures of greater simplicity and better symmetry can be obtained by welding.

Welding has the following disadvantages:

1. Defects in welds may not be discovered and corrected.

2. Deposited metal is similar to cast metal and may be low in ductility, shock resistance, and endurance limit.

3. Stresses due to non-uniform heating and to shrinkage may cause difficulties in assembling.

4. Base metal adjacent to weld may be injured by high temperatures, producing coarse grain size.

5. High-carbon steel cannot be used since welds are brittle and unreliable.

6. Sudden changes in section may cause stress concentrations.

QUESTIONS

1. What is steel?

2. Describe the cementation and crucible processes for manufacturing steel.

3. Sketch a Bessemer converter, indicating approximate dimensions.

4. Describe the Bessemer process, and state how impurities in the charge are removed.

5. In American practice what are the usual limits of composition of Bessemer pig iron? Why should at least 1.0 per cent of silicon be required? Why is a low phosphorus content necessary?

6. Why does the metal not cool off considerably during an acid Bessemer blow?

7. What is the function of a recarburizer?

8. How is steel deoxidized?

9. State some important differences between the acid and basic Bessemer processes.

10. What is the fundamental distinction between the open-hearth and the Bessemer processes?

11. Draw a diagram of a regenerative open-hearth furnace which utilizes producer gas as a fuel.

12. Describe the essential steps in the reduction of pig iron to steel in the basic open-hearth process.

13. Compare, in tabulated form, iron and steel making by: blast furnace, acid Bessemer process, basic open-hearth process, crucible process, and electric refining process as to the following particulars:

(*a*) Materials of the charge.
(*b*) Order in which materials of charge are placed in furnace.
(*c*) What flux is used.

(*d*) How impurities are removed.
(*e*) How recarburized.
(*f*) Characteristics of resultant product.

14. Compare the advantages and disadvantages of the acid Bessemer process and the basic open-hearth process.

15. Discuss the applications and limitations of electric refining processes.

16. A pig iron has the following impurities: carbon 3.5 per cent, silicon 0.8 per cent, manganese 1.2 per cent, phosphorus 2.5 per cent, sulfur 0.15 per cent. State the process you would choose to produce good steel of 0.5 per cent carbon content from this pig iron.

17. Indicate (*a*) the steel process that would give the cheapest structural steel, (*b*) the steel process that would give the best structural steel, (*c*) the cheapest method of producing a small amount of tool steel of a special analysis, and (*d*) the cheapest method of producing a good-quality carbon steel from scrap steel and iron of varying composition. State the reasons for your choices.

18. Describe the steps in making rolled-steel shapes from the casting of the ingots to the finished product.

19. Name and describe three types of rolling mills.

20. Compare the action of the steam hammer with that of the hydraulic press for mechanical working of steel.

21. Discuss in general terms the effects on the mechanical properties of hot-working and of cold-working of steels.

22. Explain the slip-interference theory.

23. Name and describe four defects in ingots.

24. Sketch from memory the iron-carbon equilibrium diagram.

25. Distinguish between delta, gamma, beta, and alpha iron.

26. (*a*) Explain what takes place when a 0.4 per cent carbon steel is cooled slowly from austenite at about 1000° C. to room temperature. Sketch the microstructure of this steel at ordinary temperature.

(*b*) Do the same for a 1.2 per cent carbon steel.
(*c*) Do the same for a 0.83 per cent carbon steel.
(*d*) What percentage of pearlite would each of these steels have?

27. Discuss the principal characteristics of steels of the following structures: austenite, martensite, troostite, sorbite, ferrite, cementite, pearlite, and spheroidized cementite.

28. Distinguish between hardening, tempering, annealing, and normalizing. What are the chief functions of each?

29. Discuss the importance of control of grain size of steel.

30. What are the differences in microscopic structure and physical properties between a steel of 1.0 per cent carbon content heated to 800° C. (1472° F.) for 30 minutes and cooled slowly and a similar steel heated to 1000° C. (1832° F.) for the same length of time and cooled in a similar manner?

31. How would you heat-treat a 0.4 per cent carbon steel casting to refine the grain and produce a soft steel that would be easy to machine?

32. How would you heat-treat a steel forging of 0.6 per cent carbon content to produce a troostitic steel of good grain structure?

33. The rough forging for an automobile crankshaft is coarse grained and full of forging strains. The metal is plain carbon steel with 0.4 per cent carbon. Indicate the heat treatment you would select to produce a fine-grained sorbitic structure in this forging. Tabulate the components of the microstructure occurring at each stage in the treatment.

34. Describe the process of case-hardening, and state the chief characteristics of case-hardened steels.

35. Describe the manufacture and uses of steel castings.

36. What are the properties of ingot iron? How is it manufactured? What are its uses?

37. State in general terms the effects of carbon on the strength, ductility, hardness, and elastic properties of steel.

38. What are the effects of silicon, manganese, phosphorus, and sulfur on the mechanical properties of steel?

39. Discuss the magnetic properties of steel.

40. How can transverse fissures in steel rails be detected?

41. Describe the electric arc and the oxyacetylene methods of welding.

42. What method of welding would you choose for the following types of construction: (*a*) hull of a steel ship, (*b*) structural steel frame of a building, (*c*) repair of a broken stern post of a ship, (*d*) butt welds in steel pipe, and (*e*) exterior surfaces of streamlined railroad cars consisting of sheets of 18-8 chromium-nickel alloy steel?

43. State the advantages and disadvantages of welding as compared with riveting.

44. Describe the methods used in inspecting and testing welds.

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CHAPTER VII

WROUGHT IRON

130. General. The definition of wrought iron given by the American Society for Testing Materials is: "A ferrous material, aggregated from a solidifying mass of pasty particles of highly refined metallic iron, with which, without subsequent fusion, is incorporated a minutely and uniformly distributed quantity of slag."

Wrought iron is a two-component metal composed of high-purity iron and iron silicate, which is an inert glass-like slag. Wrought iron usually contains less than 0.12 per cent carbon. The slag is associated physically with the iron in contrast to chemical or alloy relationships which generally exist between the constituents of other metals.

The slag content varies from about 1 to 3 per cent in finished wrought iron. The slag is distributed throughout the iron in the form of threads or fibers which extend in the direction of rolling and are so thoroughly distributed throughout the iron that there may be 250,000 or more per square inch of cross-section.

131. Wrought Iron as a Material of Engineering Construction. Previous to 1855, wrought iron was the most important metallic material for general structural and construction purposes, its strength, toughness, ductility, and forgeability making it available for many purposes which could not be served by cast iron.

The introduction and rapid decrease in cost of Bessemer and open-hearth steel in the latter part of the nineteenth century greatly decreased the use of wrought iron. It has, however, certain properties among which are resistance to corrosion and repeated stress that will always class it as a material of importance in engineering construction. A perfected process for its production has been developed which will greatly reduce its cost. Its principal uses are as a material for general forging operations, particularly where welding is involved, as rolled rods and bars, as wire, as welded pipe, and as a metal for roofs and sides of buildings, for tanks, etc.

THE MANUFACTURE OF WROUGHT IRON

132. The Puddling Process. The puddling process consists in the melting of a grade of pig iron known as forge pig, in the hearth of a reverberatory furnace which is lined with iron oxides, resulting in the elimination of most of the carbon, silicon, manganese, phosphorus, and sulfur present in the charge by oxidation. The metal becomes pasty toward the end of the process, owing to the decreased fusibility of the purer iron, and is removed as a plastic ball from which the slag must be removed as completely as possible by squeezing or hammering. The resultant puddled bloom is rolled into large "muck bars." The bars are cut into short lengths, piled up in bundles which are wired together, heated to a white heat, and rolled down to a smaller size called "merchant bars."

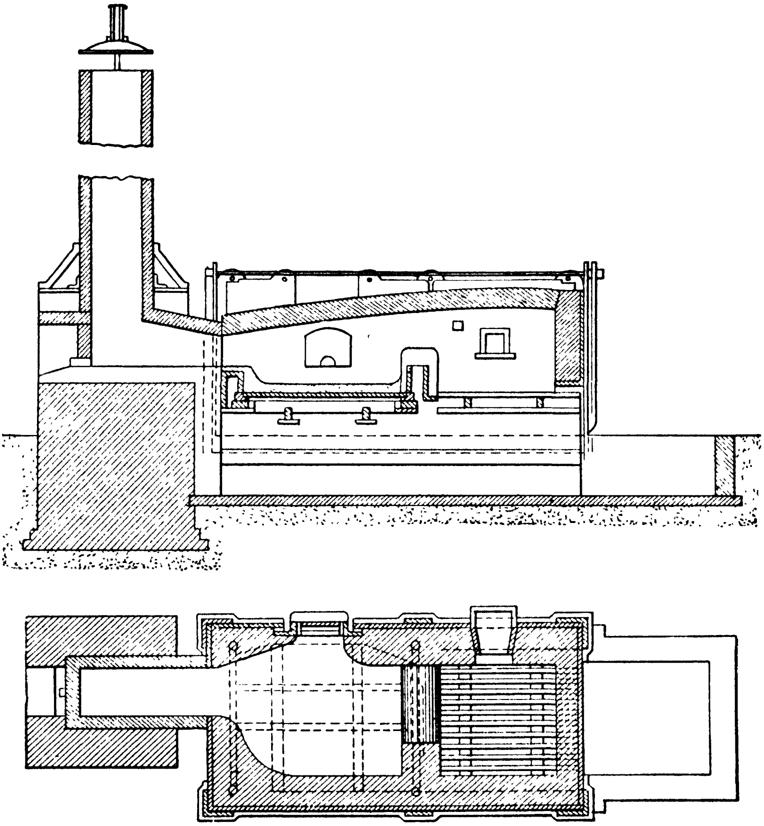

FIG. 49.—500-lb. Puddling Furnace.

133. The Puddling Furnace. The puddling furnace is a rectangular masonry structure lined with firebrick and tied together by steel tie rods and iron plates and buck stays. Fig. 49 illustrates a common type of puddling furnace. The furnace is of the reverberatory type, the heat depended upon to bring the working chamber to the desired temperature being largely that which is reflected from the sloping firebrick roof of the melting chamber, the fuel being burned in a separate compartment out of contact with the metal.

The fuel is usually a bituminous coal which burns with a long flame. It is introduced through a firing hole in the front wall. The large working door in the front wall of the working chamber has a heavy iron projecting sill and is normally closed by an iron-bound slab of brickwork which is suspended in place and balanced by a counterweight. A small opening in the lower edge of this slab affords an opportunity for the puddler to insert his rabbling iron to stir, or rabble, the charge. The slag is tapped off when necessary through a taphole provided below the working door.

Mechanical puddling furnaces are sometimes used to avoid the severe manual labor involved in the hand process.

134. The Iron Used. The pig iron commonly used for puddling is a grade known as forge pig. Its composition is from 1.00 to 1.50 per cent silicon, 0.25 to 1.25 per cent manganese, not more than 1.00 per cent phosphorus, and not more than 0.10 per cent sulfur. Comparatively high silicon is desired in order to provide sufficient slag to cover the bath of metal and prevent excessive oxidation of the iron. Manganese need not be carefully watched, because it is largely removed in the process. This small percentage of manganese is one of the means available for the determination of wrought iron from steel, which usually contains an appreciable amount of this element. Phosphorus, and particularly sulfur, are not completely removed, and must therefore be kept fairly low, although their injurious effect upon the quality of the iron is by no means as marked as upon that of steel.

The weight of the charge varies according to the size and type of furnace. Ordinary single furnaces handle from 200 to 600 pounds of pig; large furnaces, or double furnaces built in pairs without a dividing wall, may handle as much as 1500 pounds per charge. Charging is usually done by hand, the pig iron being thrown in through the firing door.

135. Furnace Operation. The furnace having been charged and a melting temperature attained, the subsequent process may be considered in four stages, which merge into one another.

The Melting-down Stage. The pig iron gradually becomes red hot and is turned about by the puddler to insure uniform heating. The more fusible slag begins to melt within 20 minutes, and in the course of half an hour the pig iron will have become completely melted down. During this stage the oxidation of the metalloids begins. The first to be oxidized is the silicon, followed by the manganese, and later by the phosphorus and a small part of the sulfur. The oxides leave the metal and join the slag. During this stage most of the silicon and manganese are thus eliminated, together with a small proportion of the phosphorus and a very small proportion of sulfur.

The Clearing Stage. During this stage, which occupies only about 10 minutes, it is usually necessary to add ore or mill scale, thus making the slag still more basic, and to close the dampers to cool the furnace sufficiently so that the carbon will not be oxidized before the phosphorus and sulfur have been disposed of. Very vigorous rabbling is necessary to promote oxidation by intimate contact between the pig iron and the fettling. During this stage the removal of silicon and manganese is almost completed, and a considerable further amount of phosphorus and sulfur is eliminated.

The Boiling Stage. This stage is principally characterized by the removal of carbon, through the agency of the fettling first, and later by the oxygen of the air. The ferric oxide is reduced by the carbon with the formation of carbon monoxide gas which bubbles to the surface, causing the boiling appearance characteristic of this period. It is especially essential that the slag be very strongly basic at this time, as it will otherwise be unable to retain the oxides of phosphorus and sulfur which the carbon monoxide might so easily reduce.

The carbon monoxide is burned by the oxygen of the air to form carbon dioxide, resulting in the appearance of the light yellow flames at the surface of the bath, called "puddler's candles." The expansion of the bath during the boil causes its level in the hearth to rise greatly, and a considerable amount of slag escapes through the open slag hole.

During the boil the puddler continues to rabble the mass vigorously, and after about 20 minutes the metal begins to "come to nature," i.e., non-fluid iron begins to collect in patches in the bath and on the surface in a pasty condition, owing to its lesser fusibility in its now nearly carbonless condition. Great care is required upon the part of the puddler to prevent this pasty iron from becoming chilled by sticking to the hearth, or oxidized by exposure above the slag. At the end of 20 to 30 minutes, all the metal will have come to nature and the removal of carbon will have reached its limit. A further quantity of phosphorus and sulfur will have been eliminated during this stage.

The Balling Stage. When all the metal has come to nature, the balling stage begins. The puddler carefully gathers all the pasty metal into one mass, which he subsequently subdivides into portions of such size as he is able to withdraw from the furnace. Each portion is worked into a ball and welded together as completely as possible. The balls are rolled up under the protection of the fire bridge to prevent excessive oxidation of the iron before being withdrawn. The balls are finally gripped with tongs and drawn out of the door over the fore plate and taken to the squeezers as quickly as possible. The usual weight of these "puddle balls" is between 100 and 200 pounds.

The balling stage requires about 20 minutes altogether. It is characterized by no chemical changes, but the furnace temperature must be maintained as high as possible in order that the puddle balls may be hot enough so that the slag will still be very fluid when they reach the squeezer.

136. The Aston Process. This process, a recent development in the manufacture of wrought iron, has three essential steps:

(1) Melting and refining the base metal.
(2) Producing a molten slag of proper composition.
(3) Granulating or disintegrating the base metal and mechanically incorporating with it the desired amount of slag.

Bessemer pig iron is melted in a cupola, tapped into ladles where it receives a special desulfurizing treatment, and is then refined in a Bessemer converter until most of the oxidizable impurities have been removed. The refined metal is not recarburized. It is then poured into the ladle of the processing machine.

Iron oxide and sand are fused in an open-hearth furnace to form an iron silicate slag. The molten slag is poured into a ladle which is placed on a ladle car and moved directly below the processing machine.

The key operation which is called "shotting" consists of pouring the molten refined iron at a temperature of about 1540° C. (2804° F.) from the ladle of the processing machine into the ladle containing the molten slag at a temperature of about 1260° C. (2300° F.), as is shown in Fig. 50. The processing machine is oscillated as well as moved forward and backward to insure a uniform distribution of the refined metal into the slag. The refined iron has a freezing point of about 1480° C. (2696° F.) while the slag solidifies at about 1120° C. (2048° F.). Since the slag is maintained at a temperature considerably lower than the freezing point of the iron, the iron is continuously and rapidly solidified. The liquid iron contains large quantities of gases in solution, but, when the metal solidifies, the gases are no longer soluble in it and escape. The solidification of the iron when it strikes the slag occurs so swiftly that the gases go off in the form of many small explosions of sufficient force to shatter the metal into small fragments which settle to the bottom of the slag ladle. Since the iron is at a welding temperature of about 1370° C. (2498° F.), and owing to the fluxing action of the siliceous slag, these fragments cohere to form a sponge-like "puddle ball" of large size, consisting of pea-sized globules of pure iron coated with silicate slag.

The resulting mixture is similar to that produced by the puddling process but is much more uniform as regards the character and distribution of the slag. The ball produced, which is much larger than that from the puddling furnace (6000 pounds or more), is handled in the same general manner by squeezing and rolling. The Aston process makes it possible to produce high-grade wrought iron in large quantities and at a much lower cost than by the puddling process. This reduction in cost will undoubtedly increase the use of wrought iron in fields where resistance to corrosion, repeated stress, and shock are of importance.

FIG. 50. — Key Operation of Pouring Molten Iron from Ladle into the Ladle Containing Molten Slag.

137. Removal of Slag. The puddle ball produced in the puddling furnace or in the Aston process is a very loosely agglomerated mass of pasty iron and slag. This slag must be removed as far as possible by mechanical means, and the iron compacted and welded together by squeezing or shingling.

A common type of squeezer consists of a wheel, mounted on a vertical axis and revolving within an encircling cylinder of cycloidal form. Both wheel and cylinder have corrugated surfaces. The puddle ball is introluced at the point where the space between the two surfaces is a maximum, and the rotation of the inner wheel causes the ball to roll as it is carried around the annular space which is constantly decreasing in width. When the ball is finally ejected a large part of the slag has been excluded and the metal has been compacted by the kneading and squeezing. The larger ball produced by the Aston process is handled in a specially designed press of large dimensions.

The puddle ball may also be shingled, i.e., forged down by some type of power hammer. The steam hammer is usually employed in shingling. Between blows, the puddle ball is constantly turned by the operator until it is thoroughly welded together and the slag largely excluded.

The compression of the porous mass of metal, either in squeezing or shingling, results in a considerable rise in temperature of the mass, which favors the expulsion of the slag by retaining it in a very fluid condition.

138. Rolling-mill Operations. The puddled blooms from the squeezer or the shingling are immediately transferred to the rolling mill wherein the finished bar or shape is produced. The bloom is first passed through a bar mill which reduces it to rectangular muck bars 2 to 4 inches thick. These muck bars are then cut into strips which are piled up, tied with wire, reheated to a welding heat, and again rolled down to form merchant bars. A further quantity of slag is squeezed out in rolling.

Bars that have been piled and rerolled are commonly called merchant bar or "single-refined iron"; when they are subjected to a second piling, heating, and rerolling, "double-refined bar" is produced. The effect of repeated rerolling is principally the further elongation of the strands of slag in the direction of rolling, thereby rendering the iron still more fibrous in its structure. No advantage is gained by piling and rolling more than three times. The final rolling is usually done in a merchant bar mill where a series of passes through the rolls serves gradually to reduce the bar to the desired size and shape.

The larger size and better slag distribution of the ball produced by the Aston process eliminate several of the steps required in the puddling process, and the solid rectangular bloom is immediately rolled to the desired billet size. These billets are then reheated and rolled into plate, skelp, bars, rods, etc.

PROPERTIES AND USES OF WROUGHT IRON

139. Composition and Constitution. The composition of wrought iron approaches that of pure iron very closely. The usual impurities—carbon, silicon, phosphorus, sulfur, and manganese—are always present in small amounts, in addition to the slag which is invariably present. Wrought iron is a composite material consisting of an intermingling of high-purity iron base metal and siliceous slag, and the impurities are distributed between the metal and the slag. Table VII gives the limits which are seldom exceeded in high-quality wrought iron and also shows typical analyses of high-quality wrought iron and very pure Swedish charcoal iron.

TABLE VII

ANALYSES OF WROUGHT IRONS

	High-quality Wrought Iron, Upper Limit, per cent	High-quality Wrought Iron, Typical Analysis, per cent	Very Pure Swedish Charcoal Iron, per cent
Carbon	0.10	0.04	0.050
Silicon	0.20	0.10	0.015
Phosphorus	0.25	0.10	0.055
Sulfur	0.05	0.03	0.007
Manganese	0.10	0.05	0.006
Slag	3.25	2.75 to 3.25	0.610

The constitution of wrought iron is quite simple as compared with that of cast iron, because of the very low percentages of carbon and other impurities in the iron. The great bulk of the material is nearly pure ferrite contaminated with small amounts of silicon, phosphorus, etc. The appearance of a longitudinal section of wrought iron under high magnification is shown in the photomicrograph of Fig. 51. The slag appears as many irregular black lines of varying thickness, and the crystalline nature of the pure iron can also be plainly seen. The pho-

FIG. 51.—Longitudinal Section of Wrought Iron Showing Duplex Structure of Slag 100×. (Homerberg.)

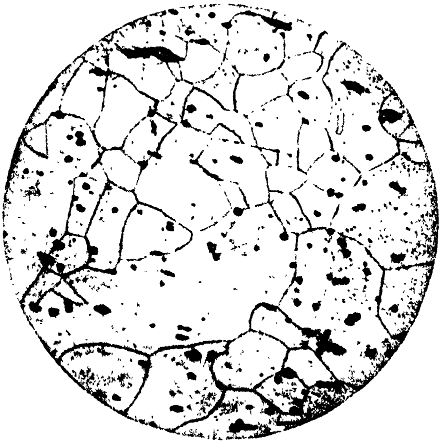

FIG. 52. — Transverse Section of Wrought Iron 100×. (Homerberg.)

tomicrograph of Fig. 52 shows the appearance of the transverse section of wrought iron. The structure is in every way similar to that seen in the longitudinal section except that the slag here appears as irregular dark areas corresponding to the cross-section of the slag fibers.

140. Tensile Strength. The tensile strength of a given wrought iron is dependent to a considerable extent upon the direction of stress with respect to the "grain" of the iron. This is to be expected, since the continuity of the metal in a direction transverse to the direction of rolling is interrupted by numerous strands of slag which are comparatively weak. The tensile strength of wrought iron in a transverse direction has usually been found to be between 0.6 and 0.9 of the strength in a longitudinal direction. It will therefore be safe to assume that this strength is about three-fourths the strength in the direction of rolling. The ductility is also appreciably greater in a longitudinal direction than in a transverse direction, but the yield point is practically the same in either direction. Typical physical properties of wrought iron in the longitudinal and transverse directions are given in Table VIII.

TABLE VIII

LONGITUDINAL AND TRANSVERSE TENSILE PROPERTIES OF WROUGHT IRON

Property	Longitudinal	Transverse
Tensile strength, lb. per sq. in..	48,000–50,000	36,000–38,000
Yield point, lb. per sq. in......	27,000–30,000	27,000–30,000
Elongation in 8 in., per cent...	18–25	2–5
Reduction of area, per cent...	35–45	3–6

The specifications of the American Society for Testing Materials prescribe the tensile properties as given in Table IX.

TABLE IX

A.S.T.M. SPECIFICATIONS FOR TENSILE PROPERTIES OF WROUGHT IRON

Longitudinal Properties—Minimum Requirements

Property	Pipe	Refined Bars	Double Refined Bars	Forgings	Rivet Rounds	Plates	Special Forming Plates (maximum transverse ductility)
Tensile strength, lb. per sq. in.................	40,000	45,000–48,000	46,000–52,000	45,000	47,000	48,000	39,000
Yield point, lb. per sq. in...	24,000	25,000	27,600–31,200	22,500	28,200	27,000	27,000
Elongation in 8 in., per cent	12	16–20	25–30	24[1]	24–28	14	8 (either direction)
Reduction of area, per cent			40–48	33			

[1] Four-inch gauge length.

During recent years the development of rolling procedure has tended to equalize tensile strength and ductility in the two directions. This development has an important bearing on the use of wrought-iron plates for applications where the metal must be formed in more than one direction, as in flanged and dished tank heads.

The modulus of elasticity of wrought iron is about 29,000,000 pounds per square inch for all the different grades.

141. Relationship between Tensile Properties of Wrought Iron and Reduction in Rolling. A fairly definite relation exists between the tensile properties of wrought iron and the amount of reduction in rolling. It is often asserted that the strength of wrought iron is inversely proportional to the cross-sectional area. It is probable, however, that this is true only so far as the smaller sizes represent a greater percentage reduction in rolling from the original pile of muck bars. Extensive tests made at the Watertown Arsenal show that practically the same tensile properties are shown by all sizes of wrought-iron rods provided only that the ratio of finished size of bar to size of pile is kept constant.

142. Effect of Overstrain and Cold Work. The effect of previous straining of wrought iron upon the elastic limit and ultimate strength, as revealed by subsequent test, is to raise the elastic limit and increase the ultimate strength provided the metal has been allowed to rest after strains. The magnitude of the change effected will be dependent upon the extent to which the previous straining was carried beyond the elastic limit of the material in its original condition.

Cold-working of wrought iron, i.e., deforming it by rolling, hammering, or pressing, at temperatures below about 690° C. (1274° F.), affects the structure and the mechanical properties of iron in much the same way as straining it beyond the elastic limit. The elastic limit is considerably raised, the ultimate strength is slightly raised, and the elongation or ductility is usually lowered.

143. Compressive Strength of Wrought Iron. The properties shown by wrought iron in compression do not differ materially from its tensile properties. Its elastic limit, ultimate strength, and modulus of elasticity are about the same in compression as in tension, provided that the ratio of length to radius of gyration of the cross-section of the test specimen does not approach the point where lateral flexure occurs.

The compressive strength of wrought iron is between 45,000 and 60,000 pounds per square inch if the length is short in proportion to the radius of gyration. Usually, however, this proportion is too great to make it possible to disregard flexure, and the ultimate compressive strength must be taken to be only equal to the stress at the yield point, or from 25,000 to 35,000 pounds per square inch, according to the character and condition of the iron.

All the considerations discussed above with reference to the modification of tensile properties by variations in the amount of reduction in rolling, heat treatment, previous straining, etc., apply with equal force to the compressive strength.

144. Shearing Strength of Wrought Iron. The resistance of the material to shearing stresses will be less on a plane parallel to the direction of the "grain" than on one that cuts the fiber of the iron transversely. The shearing strength on a transverse plane is often twice that shown on a longitudinal plane.

The actual shearing strength shown by tests is variable, but in general will be from 20,000 to 35,000 pounds per square inch on a longitudinal plane and from 30,000 to 45,000 pounds per square inch on a transverse plane.

145. Wrought Iron vs. Steel. The fibrous character of wrought iron is often used as a basis for differentiating wrought iron from low-carbon steel in the *nick-bend* test, wherein the bar to be tested is nicked with a sharp chisel and bent cold with the nick at the outside of the bend. Steel snaps sharply after a small bend, but wrought iron tears gradually with a distinctly fibrous or "woody" fracture as shown in Fig. 53.

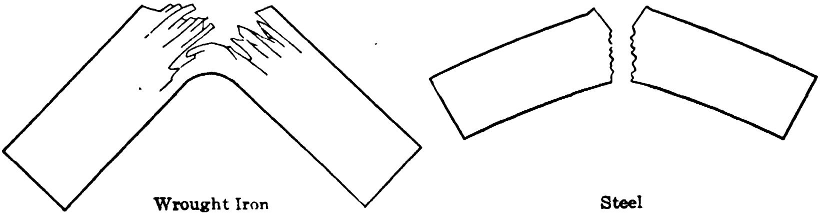

FIG. 53.—Nick-bend Test.

Wrought iron may also be distinguished from steel by means of the fact that steel nearly always contains an appreciable amount of manganese whereas wrought iron usually contains very little of this element. The presence of slag in its characteristic lines (see Figs. 51 and 52) also distinguishes wrought iron, as steel should contain practically no slag. The presence of slag can also be determined by a deep acid etch since the slag fibers cause the surface to become black.

146. Fatigue Resistance. Wrought iron shows good resistance to fatigue fracture, or progressive failure of the crystals. It is claimed that the slag fibers serve to minimize stress concentration and to deflect the path of the slip lines. Wrought iron has a good service record with respect to resistance to the effects of constant vibration and sudden shock.

117. Resistance to Corrosion. Corrosion resistance of wrought iron is attributed to the purity of the iron base metal, to freedom from segregated impurities, and to the presence of the glass-like slag fibers. Wrought iron has a good record of durability under actual operating conditions in various kinds of service.

Under some conditions where corrosion is a factor, the life of metals can be increased by the application of a protective coating such as paint or galvanizing. The surface of wrought iron is microscopically rougher than that of most metals and consequently provides good anchorage for paints. Because of the slag fibers, the natural roughness of a wrought-iron surface is accentuated by pickling with acid prior to galvanizing with molten zinc. As a result, wrought iron will take on a heavy zinc coating.

148. The Welding of Wrought Iron. One of the valuable properties of wrought iron is the comparative ease with which it may be welded. Its superiority is due largely to its comparative purity, since all impurities, especially carbon, silicon, and sulfur, reduce weldability in a marked degree. The general use of welding as a means of fabrication makes this an important characteristic. Any of the methods of welding, such as oxy-acetylene, electric-arc method, or hammer-welding, may be employed for wrought iron.

The high degree of purity of the base metal in wrought iron makes its fusion temperature somewhat higher than that of other common ferrous metals, and for that reason it should be worked hotter for best results. The slag content acts as a natural flux, thus serving as an important factor in producing a strong, uniform weld.

In gas welding, the procedure to employ with wrought iron is the same as that for mild steel, except that heating should be continued for a slightly longer period in order to attain the proper temperature. When using the electric metal arc process, the best results are obtained when the welding speed is decreased slightly below that suitable for the same thickness of mild steel. In welding light sections where there is a possibility of burning through the material, it also may be necessary to employ a slightly lower current value. Excessive penetration into the face of the parent metal is unnecessary and undesirable. The penetration should be no greater than that required to secure a sound bond between the deposited metal and the parent metal. The slight modifications in the procedure for electric fusion welding that have been indicated fall well within the normal operating range of standard equipment. Any good-quality welding rod, either coated or bare, can be used in welding wrought iron.

149. Forming, Machining, and Threading. Forming of wrought iron may be done either hot or cold, depending on the severity of the operation. Threading and machining operations are readily accomplished with wrought iron on account of its fibrous structure and the softness of the base metal.

150. Uses. For about 25 years prior to the introduction of the Aston process in 1930, the principal uses of wrought iron were for standard pipe, tubular products, bars and forging stock; since then wrought iron has been used for structural shapes, plates, sheets, welding fittings, rivets, and special pipes and tubes. Wrought-iron products are used in building construction, public works construction, and for the railroad, marine, and petroleum industries.

151. Nickel-alloy Wrought Iron. The development of the Aston process has made possible the manufacture of nickel-alloy wrought iron. Up to 5 per cent nickel may be used, but for most practical purposes 1.5 to 3 per cent nickel is satisfactory. The nickel is added to the molten wrought iron.

The comparative typical physical properties of unalloyed and 3 per cent nickel wrought iron in the same class of product are given in Table X.

TABLE X

TENSILE PROPERTIES OF NICKEL WROUGHT IRON

Property	Unalloyed Wrought Iron	Nickel Wrought Iron
Tensile strength, lb. per sq. in..	48,000	60,000
Yield point, lb. per sq. in......	30,000	45,000
Elongation in 8 in., per cent....	25	22
Reduction of area, per cent.....	45	40

It will be noted that the addition of nickel increases the tensile strength 25 per cent and the yield point 50 per cent without a marked decrease in the ductility. In these respects nickel-alloy wrought iron is similar to nickel-alloy steel. (See Art. 245.) The properties of nickel-alloy wrought iron can be improved by heat treatment. Nickel-alloy wrought iron has good impact strength at sub-zero temperatures.

QUESTIONS

1. Distinguish between wrought iron and steel.

2. Describe the puddling process of producing wrought iron. Is the puddling furnace operation acid or basic? Why does the wrought-iron metal form in a pasty condition?

3. Describe the Aston process.

4. Give a typical analysis of high-quality wrought iron.

5. Sketch the photomicrograph of a longitudinal section of wrought iron.

6. Discuss the relationship between the strength of wrought iron in tension and also in shear with respect to the direction of rolling.

7. Discuss the fatigue-resistance and corrosion-resistance properties of wrought iron.

8. Compare the welding processes for wrought iron with those employed for mild carbon steel.

9. State typical uses of wrought iron.

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CHAPTER VIII

CAST IRON

152. General. Cast iron differs considerably both in chemical composition and in physical characteristics from wrought iron and steel. It possesses a very complex constitution which is subject to variation with but slight changes in details of manufacturing processes. It is comparatively coarsely crystalline in structure, possesses considerable hardness but lacks toughness, melts readily and passes suddenly into a very fluid state, in which it will take a good impression of a mold.

Cast iron is used to a certain extent for columns and posts in buildings, for column bases, bearing plates, and innumerable minor structural parts. In machine construction it finds a wide field of application, for it can be cast in complex forms at a comparatively low cost.

A small number of iron castings are made by running the metal into molds as it comes from the blast furnace. Ingot molds, for instance, are made in this way at steel works. The variability of the blast-furnace product, however, limits the use of these direct castings. The bulk of all the iron used as cast iron is remelted either in the *cupola furnace* or the *air furnace* before being cast in molds.

The process of remelting the iron in the cupola resembles the process of melting ore in the blast furnace, except that the reducing action of the blast furnace is not present. The only office of the air blast is the oxidation of the fuel of the charge. Remelting in the air furnace bears no resemblance to cupola melting, since the charge is melted in a hearth out of contact with the fuel. The heat is supplied by radiation and reflection from the flame of a soft-coal fire maintained in a firebox adjoining the hearth, or from a burner using powdered coal or fuel oil.

MANUFACTURE OF CAST IRON

153. Raw Materials. *Foundry Pig Iron.* Nearly all pig irons for foundry purposes are bought by analysis, the content of silicon and sulfur being specified, and sometimes also the total carbon, manganese, and phosphorus.

In addition to the irons properly classed as foundry pig irons, Bessemer pig, ferrosilicon, and a few other special pig irons are used at times to bring the composition of the cast iron within the required limits.

Scrap Iron. The term "scrap iron" designates that considerable portion of the iron charged into the furnace which has been remelted one or more times. It consists mainly of castings discarded after having been in service, but includes also defective castings, gates, sprues, etc. Some classes of castings are made without any scrap. For others, the amount sometimes runs as high as 30 or 40 per cent.

The Flux. The office of a flux in the melting of iron is to absorb and carry off in a slag the non-metallic residue of the iron and the ash of the fuel, and to assist in the removal of sulfur. Since the impurities in the charge of the melting furnace constitute only a very small proportion when compared with the amount present in the charge of the blast furnace, the percentage of flux required is correspondingly small. The requirements vary greatly, but in general will average in the neighborhood of ½ to 1½ per cent of the weight of the iron.

The flux is calcium carbonate, usually in the form of limestone, but oyster shells, marble chippings, dolomite, etc., are sometimes used, and a portion of fluorspar (CaF_2) is often added to obtain a more liquid slag.

The Fuel. The fuel in iron melting serves simply as a source of heat.

Coke is the most common fuel in the cupola, although a mixture of coke and anthracite coal is sometimes used. The air furnace requires a long-flaming bituminous coal or gas.

The fuel requirements depend upon the character of the castings being made, small and thin castings requiring a hotter metal than large ones.

THE CUPOLA

154. The Cupola Furnace and Its Equipment. The cupola in its essential arrangement is really a small blast furnace, operated under a very much lower blast pressure, and intended only to melt the charge without any attempt being made to attain reducing conditions. The cupola is used for most foundry purposes in the production of gray-iron castings and for melting iron for steel furnaces.

The type of cupola shown in Fig. 54 is representative of those used in foundries. It consists of a vertical cylindrical shell of wrought iron or steel, lined with firebrick set in fireclay grout. The structure is supported on columns about 4 feet from the floor. The size of the cupola is quite variable, ranging from about 22 inches inside diameter to about 100 inches. The height is dependent upon the diameter, the usual practice being to locate the charging door at a height above the bottom plate equal to 3½ to 4 times the internal diameter. The height of the stack above the charging door is governed by considerations of draft.

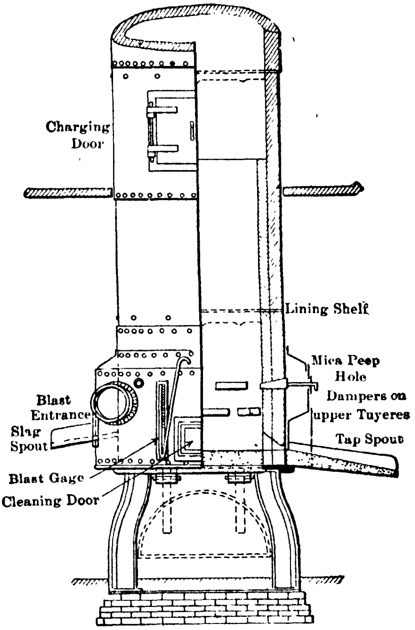

FIG. 54.—Foundry Cupola.

The air blast enters the crucible through tuyères leading from the wind belt, or air chamber, which surrounds the lower portion of the furnace. The tuyères themselves are not elaborately constructed, but are usually simply iron castings set in the brickwork of the lining. The tuyères are usually arranged in two horizontal rings some 12 or 15 inches apart vertically, the area of the upper tuyères being, as a rule, only a small fraction of that of the lower ones.

The slag hole is situated just below the tuyères at a height above the bottom plate governed by the amount of metal required per heat.

The bottom of the furnace consists of two or more flap-hinged castings which are normally held in position by a prop beneath. At the conclusion of a heat, or cast, the prop is knocked out, allowing all the material remaining in the furnace to be dumped.

The taphole, or spout, is located just at the level of the bed of sand which covers the bottom doors.

The air blast is generally derived by means of a positive-acting blower, usually of the two-impeller type. This type of blower is very simple, free from mechanical weakness, and capable of delivering large quantities of air under low pressures.

155. Operation of the Cupola. *Charging.* The usual method of starting a run consists of laying a bed of shavings and kindling wood on the bottom, followed by heavier wood, then fine coke, and last a charge of the regular fuel.

The tuyère doors are now opened, the shavings lighted at the front, and the fire allowed to burn up until all the fuel is well lighted. Then the tuyère doors are closed and charging is begun.

An oil torch is sometimes employed without wood kindling. Openings or flues through the coke are made directly upon the sand bed by means of thin boards, and the fuel is ignited by the torch flame entering at the front.

The bed of fuel having been properly prepared and leveled off, the charge of broken pig and scrap is carefully placed, an effort being made to fill up the interstices as far as possible and keep the charge level. The next charge of fuel is now placed on the iron, and alternate charges of iron and fuel continue until the height of the charging door is reached. When a flux is required, the proper proportion is charged on top of each bed of iron, except at the start and at the end of the heat, when it may be omitted.

The furnace is often charged 2 or 3 hours before the blast is started, but, even if the blast is put on immediately after charging the iron, iron should begin to melt and appear at the taphole within 15 or 20 minutes after starting the blast. If it does not, it indicates that the bed of coals has not been properly prepared.

When the furnace is properly operated it shows the following distinct zones of action, beginning at the bottom and proceeding upwards: The crucible zone or hearth, the tuyère zone, the melting zone, and the stack. These four zones are indicated in Fig. 55.

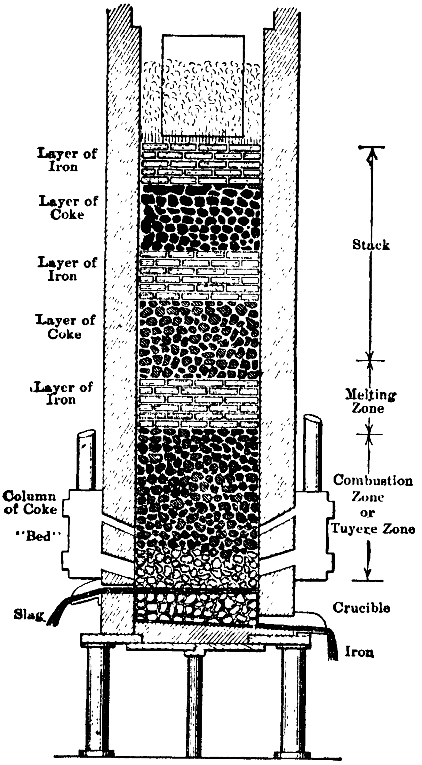

FIG. 55.—Zones in Cupola. (Stoughton.)

The crucible zone extends from the bottom up to the level of the tuyères. It serves the sole purpose of collecting and holding the molten metal and slag until tapped out.

The tuyère zone is the zone of combustion. The blast here comes in contact with the red-hot coke and rapidly oxidizes it. A column of coke always extends from the melting zone to the bottom of the crucible, and combustion occurs from the level of the molten metal to a point above the tuyères, the height of which is dependent upon the pressure of the blast.

The melting zone is situated directly above the tuyère zone. During the melting the iron is supported on a column of coke, extending to the bottom of the cupola, which is the only solid material below the melting zone. The iron as it melts trickles down to the bottom over the column of coke. Each layer of iron requires about 5 to 10 minutes to melt, and the column of coke is constantly sinking, so that the last of the iron melts several inches lower than the first. If the charges of iron and coke and the pressure of the blast are properly proportioned, each charge of iron will enter the top of the melting zone just before the last charge is completely melted at the bottom.

The stack extends above the melting zone to the level of the charging door. Its function is to contain material that will absorb heat to bring it into good condition for action in the melting zone, and to keep the heat in the melting zone as much as possible.

Duration of the Cupola Run. A foundry cupola is never run continuously, but is started anew for each casting and is "dumped" at the conclusion of the run. As a general rule, the duration of the run does not exceed 3 or 4 hours, and it cannot exceed this period if no provision is made for draining off the slag. Some large cupolas operated in connection with steel plants are run continuously for 6 days in a week, at the end of which time, if not before, it is generally necessary to stop to effect extensive repairs.

Tapping Out and Stopping In. The taphole is usually left open until the iron begins to run after the blast is started, at which time it is closed if an accumulation of metal is desired. Often the first iron is used only to warm the ladles which are subsequently to be employed in pouring the castings.

The "stopping in" is accomplished by means of the "bod" and "bod-stick." The bod is a plug made of fireclay, sand, or molding sand, molded in the shape of a cone which adheres to the enlarged end of the "bod-stick," which is simply an iron bar with an upset end. The bod is thrust in quickly to stop the flow of metal and bakes hard enough to withstand the pressure. A soft bod of molding clay and sawdust is used when the cupola is tapped and stopped very frequently.

Tapping consists simply in piercing the bod with a round iron bar provided with a pointed end. It is an operation requiring great care, since the danger of causing molten iron to spill and burn those near at hand is ever present.

THE AIR FURNACE

156. The Reverberatory or Air Furnace. The reverberatory or air furnace has natural draft and employs the principle of utilization of heat derived by reflection from the roof upon the bath of the metal.

The air furnace is principally confined to the production of white iron for malleable cast iron, but it is also used to produce irons of particular composition for special purposes.

The design of air furnaces shows many variations, but Fig. 56 shows a typical form in which coal is burned as fuel. The main portion of the furnace, the hearth (*f*), is flanked on one end by a firebox (*g*), and on the other by a flue leading to a stack (*o*). The walls of the furnace (*a*) are of very heavy brick masonry incased in iron plates (*b*), and reinforced both ways by tie rods (*c*) between buck stays (*d*).

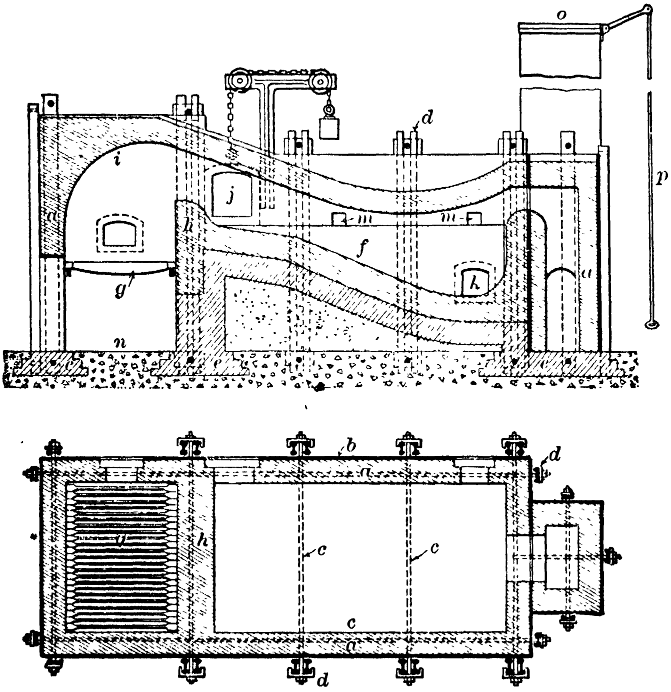

Fig. 56.—Air Furnace.

The hearth bottom is a mixture of sand and fireclay supported by brickwork built to slope downward from the fire-bridge (*h*) to the flue-bridge. The crown of the furnace is similarly inclined downward toward the stack in order to deflect the heat of the flames downward on the iron in the hearth.

The firebox is provided with iron grate bars, and fuel is introduced through a fire-door in one side wall of the firebox. Pig iron and scrap are charged in through the charging door (*j*), and holes (*m*) are provided to facilitate the skimming of the bath of metal. The spout is not shown in the figure, but is so placed as to drain the metal from the lowest part of the hearth.

Furnaces in which large amounts of iron, or bulky scrap iron, are melted often have removable sections in the crown through which the charge is lowered by cranes.

In some modern air furnaces the hard-fired iron grate firebox is replaced by a burner using powdered coal or fuel oil.

157. Operation. *The Charge.* The small scrap is first placed in the furnace hearth, followed by the flux and the pig iron or the large scrap. The furnace is either still hot from the last melt, or it is heated for some hours before charging, so that melting begins soon after the charge is placed.

Control of Melting. The temperature of the furnace is controlled by the regulation of the draft by means of a damper in the stack or stack flue, and one in the firebox. The bituminous coal burns with a long flame which sweeps through the melting chamber, the conditions being strongly oxidizing rather than reducing. A slag soon forms and covers the metal as it accumulates, so protecting it in a measure from oxidation. The slag is not drained off, but must be skimmed from time to time. The furnace man also rabbles the charge, gradually pushing the pig down into the bath.

The time required for melting is much greater than in the cupola, the actual time being dependent upon the capacity of the furnace. A 10-ton furnace will melt down a charge in 3 or 4 hours; a 30-ton furnace will require 8 or 9 hours. The fuel requirement is about one-fourth the weight of the charge, or about 25 per cent of the iron produced. The metal is tapped as rapidly as possible, and, since the hottest metal is at the top of the bath, a series of tapholes at different levels are sometimes used successively. The loss of metal due to oxidation amounts to 2 to 5 per cent of the charge.

Oxidation can be more carefully controlled by means of fuel oil or powdered coal burners. No regulation of air from the draft is required. The composition of the finished cast iron and the temperature of pouring can be accurately controlled.

158. Advantages and Disadvantages. The product of the air furnace is purer than cupola iron, since the metal does not come in contact with the fuel. This means less absorption of sulfur and less absorption of carbon, resulting in general in a higher grade and stronger iron. The process being much slower than the cupola process, it is under better control and any desired composition can be more closely approached.

The cupola, on the other hand, is a cheaper installation, requires less skilful management and is therefore cheaper to operate; the heat is more uniform, so that all the metal of a melt has more nearly the desired temperature; very hot iron is more easily obtained; the furnace can be started and stopped more readily; the fuel efficiency is greater; and there is less loss of metal through oxidation and consequent removal in the slag.

IRON FOUNDING

159. Iron Founding in General. The art of founding consists in pouring molten metal into a mold of any desired special form, which the metal assumes and retains when cold. Provision must be made for elimination of gases evolved when the iron solidifies and for shrinkage of the iron upon cooling.

The most important part of iron founding is making the molds, a process which demands considerable mechanical skill and no small amount of manual labor. No portion of the technology of iron is of more importance to the engineer and designer than a thorough understanding of the molder's art. Sand, the material generally used for molds, cannot be molded into any conceivable shape, but has certain practical limitations. For the most part, the impression in the sand of the mold is made by a pattern which must be so designed that its removal from the mold is possible. It is not so easy as it may at first appear to avoid shapes which would call for a pattern which could not possibly be removed, leaving the mold intact. Another consideration is that sand, when confined, is a comparatively unyielding material, and therefore the shape of castings must be such that the shrinkage which invariably occurs as the metal cools will not induce dangerously high internal stresses.

Without mentioning any of the other factors, it will be clear that the definite limitations of the molder's art constitute certain limitations for the engineer, and, without a practical knowledge of the former, iron castings cannot be intelligently designed.

160. Molds and Molding. The various methods of making sand molds may be divided into the following three classes of greatest importance: "green-sand molding" involves the making of an impression of the desired form, by means of a pattern, in a mold composed entirely of sand in a damp state; "dry-sand molding" involves the making of molds in damp sand by means of a pattern as in green-sand molding, after which the mold is dried in an oven until the moisture is expelled and the sand baked hard (molds made of foundry sand coated with a thin film of clay and colloidal iron hydroxide retain their form after drying); "loam molding" does not involve the use of patterns, but its application is largely confined to articles whose surfaces are surfaces of revolution, the molds being built up of brickwork covered by a layer of loamy sand in which the desired imprint is made by a "sweep." Machine molding may replace hand work by any of these methods.

A mold is usually made in two parts, the upper part being called the *cope* and the lower part the *drag*. The rectangular frame commonly used to hold the mold is called the *flask*. Patterns are many times divided into two parts. The lower part is placed at proper height in the sand in the drag, and the sand is tamped and struck off evenly at the top. The pattern is then carefully withdrawn from the sand, leaving an imprint of the pattern in it. The upper part of the pattern is similarly employed in the cope, and the cope is inverted and placed on top of the drag so that a hollow space corresponding to the casting will be formed. A passage called a *gate* is formed in the cope for pouring the metal into the cavity, and at least one passage of relatively large cross-section called a *riser* is provided to the upper surface to serve as a vent for gases and to form a reservoir of excess molten metal for the purpose of filling the casting cavity completely as the metal shrinks in cooling.

161. Patterns and Cores. Pattern-making is an art in itself, involving a considerable amount of technical skill. Patterns may in general be divided into two classes, the first of which are used to produce solid castings, the second to produce hollow ones. Usually, however, the pattern is solid, the hollow portion being formed by a core which is placed in the mold after the removal of the pattern.

The great majority of all patterns are made of wood. Brass or other metals are sometimes used for the sake of greater durability when a great many molds are to be made from the same pattern. The simplest patterns are merely solid wood duplicates of the desired castings except that an allowance of about 1/8 inch per foot is made in dimensions to compensate for the shrinkage of gray-iron castings in cooling and about 1/4 inch per foot for white-iron castings. A slight tapering known as draft is given the vertical plane surfaces in order to facilitate the withdrawal of the pattern from the mold.

The cores are usually made from a mixture of fine siliceous sand with clay or loam, which is packed in the core-box while damp. Some binder, such as flour and water, starch, molasses, linseed oil, rosin, or glue-water, is usually required to give the core strength enough to permit handling, and holes are commonly left running lengthwise through the core for the purpose of venting. When the cores are dried in an oven prior to use in a mold they are called dry-sand cores. The great majority of all cores are of this class. If a core is long, particularly if it is supported horizontally over a considerable span, it is necessary to stiffen the core by insertion of iron or steel wires or even skeleton frames of metal. A core maintains its shape while the molten metal flows around it, but the heat carbonizes the binder, destroying the bond between the sand grains and thus permitting the core to be crushed by the shrinkage of the metal without damage to the casting. Cores that are adjacent to thick parts of a casting are apt to be fused before the metal is solidified, unless protected from the heat of the slowly cooling molten metal. They are therefore often daubed with an insulating coating of blackening. For this purpose pulverized graphite or plumbago is either applied wet as a wash, dry with a brush, or shaken from a cloth bag.

162. Chilled Castings. A chilled casting is one made in a mold, some parts of which, at least, are made of iron, such portions of the mold being called "chills." The purpose of introducing chills into a mold is to convey away the heat of the molten metal rapidly, a treatment which has the effect of causing the carbon in the iron to remain in chemical combination, instead of separating therefrom in the form of graphite, as it normally does in slowly cooled castings of gray iron. The physical effect of chilling on the character of the iron is to harden it greatly for a certain depth, giving to the exterior of the iron the characteristic appearance of white iron, while the body of the casting remains a gray iron. Chilling is principally used for wearing surfaces of such castings as iron rolls and treads of car wheels.

163. Designing Castings. The following rules should be observed by the designer: (1) avoid sudden changes in thickness, (2) avoid sharp corners, and (3) avoid sharp reëntrant angles. Changes in thickness should be gradual, and sharp corners should be rounded. Reëntrant angles are particularly bad since the flow of heat at such angles is greater than on plane surfaces, causing crystals to grow slowly on a line bisecting the reëntrant angle and thus producing initial tension there. The remedy is to round off the angles. The designer should make use of fillets to avoid sharp edges. Parts of a casting should be arranged so that it can shrink without restraint.

164. Pouring the Iron. In small foundries it is usually the practice to stop molding in the middle of the afternoon and pour all the molds that have been made. For small work the metal is caught in hand ladles at the cupola taphole and conveyed to the molds by one or two men. The ladles must be heated by allowing a part of the first iron run to stand in them for a few moments before the actual pouring is begun; otherwise the ladle will chill the metal and the iron will not enter the mold at the required temperature. Practically all foundry ladles are top-pouring (i.e., the metal is poured by tipping the ladle), rather than teeming ladles, which are provided with a valve in the bottom. This necessitates the use of a bar to keep back the slag which floats on the metal and would otherwise enter the mold. Care is exercised by the molder to hold the ladle as near the pouring gate as possible to lessen the impact of the stream of metal upon the sand of the mold. The proper time to cease pouring is indicated by the appearance of the metal at the top of the riser. Each mold must be filled in one operation, and therefore when the ladle does not contain enough metal to fill a mold completely its contents are emptied into pig-beds molded on the foundry floor.

Large foundries employ traveling cranes and large ladles holding perhaps a ton or more of metal. During the filling of the molds, it is usually the practice to ignite the gas which escapes from the vent holes, thereby preventing its accumulation in the molding room.

The flasks are removed soon after the completion of the pouring, and the molds are dumped off the bottom boards in piles, from which the hot castings are hooked out and allowed to cool. The gates and runners are now broken off by a few sharp blows with a hammer and the castings removed for cleaning.

165. Cleaning the Castings. The sand which adheres to the castings is usually removed by one of three methods: rattling them in a tumbling barrel, pickling, or sand blasting.

Rattling is most commonly practiced with small castings. The tumbling barrel is simply a short horizontal cylinder mounted on trunnions. The castings are piled into the barrel, together with a quantity of abrasive material in the shape of small, irregularly shaped, hard iron stars or picks. The barrel is rotated slowly, and the falling about of the castings and the stars gradually knocks the burned sand and scale off the surfaces of the castings. This method has the disadvantage of producing a hard skin upon the castings which causes difficulty if they are subsequently to be machined.

Rattling will never completely clean any but very simple castings, and a better method consists in pickling the castings by immersion in a dilute sulfuric or muriatic acid solution. The acid attacks the iron somewhat, thereby loosening the sand and scale. Pickling in a 15 per cent solution of sulfuric or muriatic acid requires about 12 hours and must be followed by a careful washing in water. Hydrofluoric acid sometimes replaces sulfuric or muriatic acid. The former attacks the sand itself, instead of the iron, and with only about a 5 per cent solution castings may be cleaned in an hour or less.

The sand blast is the most convenient method of cleaning large castings, especially those of very irregular form, such as gears, etc. Very often the sand blast is followed by pickling.

The final operation in the preparation of castings for use consists in smoothing up the irregularities left by breaking off the gates, the "fin" formed where the metal has run between the two portions of a mold, etc. With small castings this is most readily done with an emery wheel. With larger castings chipping with a cold chisel is often necessary, and a pneumatic chipping tool is most efficient. Portable emery wheels fitted with a flexible drive are also used for this purpose.

PROPERTIES OF CAST IRON

CONSTITUTION

166. Essential Constituents of Cast Iron. Referring to the iron-carbon diagram, Fig. 41, Art. 103, it will be noted that only up to about 1.7 per cent carbon will dissolve in iron in the solid solution. This marks the limit of the steel range; beyond is the series of alloys known as cast iron, the usual carbon content of which is from 2.5 to 4.5 per cent. Neglecting the effects of other elements, the constitution of iron-carbon alloys in the cast-iron range is described.

A liquid iron-carbon alloy containing from 1.7 to 4.3 per cent of carbon separates during solidification along line *AC* into austenite (solid solution of carbide in gamma iron having a maximum of 1.7 per cent carbon at 1130° C. [2066° F.]) and a residual liquid which becomes increasingly richer in carbon. At the eutectic temperature (1130° C. [2066° F.]) the liquid contains 4.3 per cent of carbon and solidifies as the eutectic mixture, called ledeburite, which consists of a mixture of saturated austenite and cementite. When the alloy is cooled below the eutectic temperature, cementite is separated from austenite along the line *ES*. At the eutectoid (723° C. [1333° F.]) the remaining austenite is transformed into pearlite. Below the eutectoid the iron has a complicated microstructure of cementite and pearlite.

Iron-carbon alloys containing above 4.3 per cent of carbon separate during solidification along line *DC* into cementite and a residual liquid. At the eutectic the remaining liquid solidifies into ledeburite. The austenite in the ledeburite is transformed into cementite and pearlite as above described. Below the eutectoid this iron also has a complex microstructure of cementite and pearlite.

The discussion above refers to iron-carbon alloys, but the composition of cast iron is that of a complex alloy containing usually six important elements, together with other elements of less frequent occurrence. The elements invariably present are, in the approximate order of their importance, iron, carbon, silicon, phosphorus, sulfur, and manganese. In addition, copper, nickel, oxygen, and nitrogen are often present, and aluminum, titanium, vanadium, and chromium are sometimes added.

The constitution of cast iron is much more complex than the composition, because of the variety of compounds which the elements present combine to form. The most important consideration affecting the character and properties of cast iron is the carbon content and, in particular, the form assumed by the carbon, i.e., whether free as graphite, or in chemical combination with the iron as a carbide. The importance of the elements other than the iron and carbon is chiefly due to their influence upon the state assumed by the carbon.

Before the essential constituents of cast iron can be stated even in a general way the existence of three principal classes of cast iron must be recognized, the differences being due to the different states in which the carbon occurs.

Gray cast iron is that in which the carbon occurs chiefly in the graphite state.

White cast iron is that in which the carbon occurs chiefly as the carbide of iron.

Mottled cast iron is a mixture of particles of gray iron with particles of white iron. It has no special adaptation, and its production is largely unintentional.

167. Carbon in Cast Iron. When cast iron solidifies from the molten state the carbon probably remains in the combined conditions as carbide of iron, Fe_3C, which is partly free as cementite, and partly in solid solution in the iron as austenite. The Fe_3C is an unstable compound, however, and when formed at a high temperature is readily decomposed into graphite and iron.

The decomposition of the carbide with the consequent formation of graphite carbon is facilitated particularly by a slow rate of cooling and by the presence of silicon. It is retarded, on the other hand, by rapid cooling or by the presence of much sulfur or manganese.

168. Gray Cast Iron. Cast irons containing considerable amounts of graphite carbon are known as gray cast irons, because of the grayish or blackish, coarsely crystalline appearance of their fractures. This appearance is caused by the presence of many irregular and generally elongated and curved plates of graphite imbedded in the matrix of ferrite and cementite. These plates of graphite are made up of smaller plates, somewhat like sheets of mica, and may be split apart with ease. The individual sheets of graphite vary in size from microscopic proportions to one-eighth of a square inch or more in area. The characteristic structure of gray cast iron is shown in Fig. 57. The irregular dark bands are graphite plates, the intermediate area being the ferrite-cementite matrix. The actual amount by weight of graphite in gray cast iron is between 2 and 4 per cent, the combined carbon being under 1½ per cent. The volume content of graphite is much higher, however, since iron has a specific gravity about 3½ times that of graphite.

Since the strength of gray iron depends almost entirely on the matrix in which the graphite is imbedded, it follows that the strongest and hardest gray iron is that in which the matrix is wholly pearlitic. The constitution of the matrix may be varied from pearlite, through mixtures of pearlite and ferrite in different proportions, down to a practically pure ferrite. The graphite-ferrite mixture is the softest and weakest iron; the strength and hardness increase, reaching the maximum with the pearlitic gray iron.

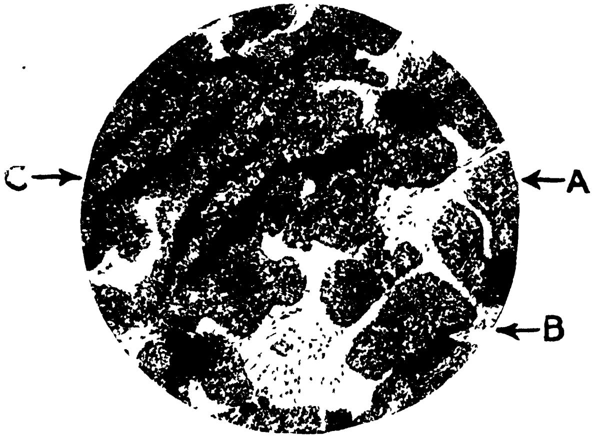

Fig. 57.—Gray Cast Iron 150×. (Homerberg.)
A Pearlite, *B* Ferrite, *C* Graphite (dark streaks).

169. White Cast Iron. Cast iron in which most of the carbon is present in chemical combination with iron as carbide of iron (Fe_3C), or cementite, is called white cast iron because of the white, highly metallic fracture which characterizes it. The ferrite and a portion of the cementite together form pearlite, so that the ultimate constitution of an iron free from graphite will be a mixture of cementite and pearlite. The appearance of white cast iron is shown in Fig. 58, in which the light areas are free cementite and the dark banded areas are pearlite.

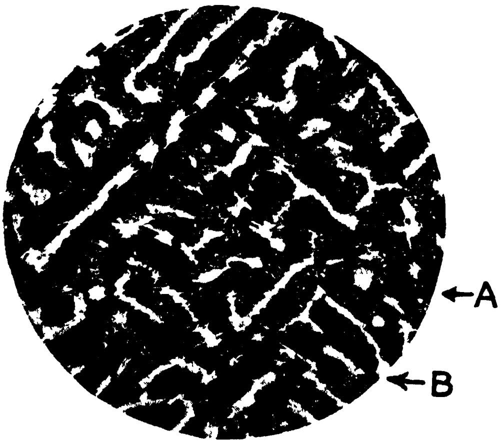

Fig. 58.—White Cast Iron 100×. (Homerberg.)
A Pearlite, *B* Cementite.

The dividing line between high-carbon steel and white cast iron lies at about 1.7 per cent carbon, but, as a matter of fact, most steels do not approach 1.7 per cent carbon and few white cast irons have less than 2.25 per cent or even 2.50 per cent carbon. The chief industrial use of white iron is as a starting point in making malleable iron (Art. 185).

170. Silicon in Cast Iron. After iron and carbon, silicon is, in its effects upon the character of the iron, the most important element present in cast iron. Silicon combines with a part of the iron to form the silicide (Fe_2Si), which forms a solid solution with the ferrite. The primary effect of silicon upon the carbon is as a precipitant, driving the carbon out of combination into the graphite form. The maximum precipitation of graphite seems to occur with about 2.5 to 3.5 per cent of silicon.

The presence of silicon causes the eutectic to consist of austenite and graphite instead of austenite and cementite. Final solidification occurs above the eutectic temperature for plain iron-carbon alloys. Further slow cooling after solidification decomposes the austenite along the lines $E'S'$ (Fig. 41), causing graphite to be formed. At the eutectoid the remaining austenite decomposes into alpha iron and cementite, forming a pearlitic structure. Very slow cooling below the eutectoid will transform the cementite into alpha iron and graphite.

When silicon is increased in amount, the solubility of carbide in austenite becomes less. Also the presence of silicon raises the temperature of the eutectoid and reduces the carbon content corresponding to the eutectoid.

Silicon in percentages below about 2.5 per cent acts, therefore, as a pronounced softener, producing soft gray iron, but larger percentages result in the formation of hard and brittle iron due to the excess of the hard, brittle iron silicide, Fe_2Si. Small percentages also produce freedom from oxides and blowholes, promote fluidity, and decrease shrinkage and depth of chill.

171. Sulfur in Cast Iron. The influence of sulfur upon the form assumed by the carbon in cast iron is the reverse of the influence of silicon. The higher the sulfur content, the higher will be the proportion of combined carbon. This tendency upon the part of sulfur is much greater than is the opposite tendency exhibited by silicon, however, a given amount of sulfur being able to neutralize about 15 times as much silicon. Sulfur, therefore, tends to produce hard, brittle, white iron.

Aside from the effect of sulfur upon the properties of iron on account of the fact that the carbon is driven into combination as the carbide, sulfur, if present as iron sulfide, FeS, possesses the power materially to affect the behavior of iron in solidifying and cooling. Only a few tenths of 1 per cent of sulfur suffice to render iron very tender at a red-heat ("red-short"), and therefore likely to check or crack if in solidifying the shrinkage causes the casting to tend to crush the sand of the mold, thus resulting in the setting up of internal stresses in the iron. Sulfur also causes solidification to become very rapid, and often is responsible for the presence of blowholes and sandholes.

Manganese, because of its great affinity for sulfur, will tend to rob the iron sulfide, FeS, of its sulfur, forming MnS, a compound which is less potent than FeS in affecting the proportion of combined carbon. A given percentage of sulfur may, in general, be neutralized by the presence of about twice as much manganese. Specifications usually limit the maximum sulfur content of gray cast iron to not more than 0.10 per cent, and often the maximum allowance does not exceed 0.05 per cent.

172. Phosphorus in Cast Iron. Chemically, phosphorus tends to increase the proportion of combined carbon, especially when the silicon is low and the phosphorus high. On the other hand, phosphorus lengthens the time of solidification, thereby affording opportunity for the precipitation of graphite. When the silicon is high, therefore, the presence of moderate amounts of phosphorus actually increases the precipitation of graphite, but when the proportion of phosphorus is very large, the chemical effect is great enough to retain the carbon in the combined form in spite of the longer period of solidification.

The presence of phosphorus in considerable amounts tends therefore to produce a hard white iron, lacking in toughness and workability, and especially lacking in shock resistance when cold. Phosphorus reduces the melting point of iron and makes it very fluid. It is therefore useful in making very thin castings where a less fluid iron will not take a perfect impression of the mold. Not more than 0.05 per cent of phosphorus is allowed in the best gray iron, though from 1.0 to 1.5 per cent is sometimes used when fluidity is more important than toughness.

173. Manganese in Cast Iron. Manganese increases the tendency for iron to hold carbon in solution and therefore increases the proportion of combined carbon, though it is much less potent in this respect than sulfur.

If no more manganese is present than is required to combine with the sulfur, forming MnS, its effect will not be to increase the proportion of combined carbon, but just the reverse, because the sulfur is taken from the sulfide, FeS, which is so powerful in causing the carbon to assume the combined form. Any additional manganese unites with carbon to form the carbide, Mn_3C, and this carbide unites with the Fe_3C, causing the cementite to be made up in part of the double carbide of iron and manganese $(FeMn)_3C$.

It appears, therefore, that manganese, up to the amount which combines with sulfur to form MnS, tends to lower the proportion of combined carbon and consequently decreases the hardness and brittleness of the iron. Any additional manganese, however, has a marked effect in causing the carbon to assume the combined form, and is therefore a hardener.

PHYSICAL PROPERTIES

174. Behavior of Iron in Cooling. *Shrinkage.* The shrinkage of cast iron is an important consideration for the pattern maker, because due allowance for shrinkage must be made in the dimensions of the pattern if the casting is to conform to the size called for by the drawings. It is also an important consideration for the designer and the founder, because the stresses set up in cooling and the consequent danger of checking are directly dependent upon the degree of shrinkage if the casting is of such a shape that its shrinkage tends to crush the sand in the mold.

With few exceptions, all metals expand upon heating and contract when cooling. The total expansion in melting a metal will correspond to its total shrinkage in solidifying and cooling. Pure iron shrinks about 0.3 inch per foot; a less pure iron usually shrinks less, because impurities, particularly carbon, in general lower the melting point.

The separation of carbon as graphite exerts a powerful influence upon the total net shrinkage of iron because of the expansion which its separation causes.

The factors that chiefly determine the amount of shrinkage are therefore the factors that chiefly control the separation of graphite, i.e., the silicon content and the rate of cooling. Moreover, since the rate of cooling is largely dependent upon the size of the castings, the shrinkage becomes largely a function of silicon content and size. This relationship is shown graphically by Fig. 59, which is based upon experiments made by W. J. Keep. The shrinkage is shown to be inversely proportional to the percentage of silicon, and for an iron of given composition the shrinkage decreases as the size of casting increases.

Other elements whose presence affects the separation of graphite, either directly or by affecting the rate of cooling, naturally have an effect upon shrinkage. Sulfur, which drives carbon into combination with iron, therefore increases shrinkage unless neutralized by other elements. Phosphorus, by lowering the rate of cooling, tends to promote the separation of graphite and decrease the shrinkage.

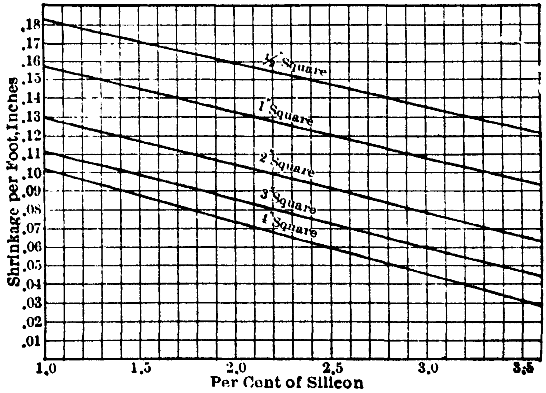

FIG. 59.—Approximate Relationship between Shrinkage, Silicon Content, and Size.

*Checking.** The tendency of iron to check while cooling is dependent upon the magnitude of the stresses caused by the contracting of the metal upon the sand, and upon the weakness of the metal at a temperature slightly above a black

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*** Development of minute cracks.**

heat. The factors that govern shrinkage, therefore, determine the stresses to which the cooling metal will be subjected, if the casting is of such a shape as to compress the sand in shrinking.

Sulfur is the most deleterious element affecting the strength of iron at a temperature just above a black heat. Phosphorus, by decreasing shrinkage, should decrease the checking of the metal, but this effect may be more than offset by the tendency of phosphorus to cause the metal to assume a coarsely crystalline structure. Manganese somewhat counteracts this last tendency upon the part of the phosphorus and therefore tends to prevent checking.

Segregation. Segregation in castings is the collecting together of impurities in spots. The primary cause of segregation is the effect of impurities in lowering the freezing point of iron. This results in forming a fluid solution which remains molten after the remainder of the metal has solidified, and runs to that part of the casting which has the loosest texture. These spots, often called "hot spots," are likely to occur in the middle of the larger sections of the casting. They are often porous, and are usually hard and brittle.

The tendency to segregation is proportional to the amount of impurities present. Phosphorus is especially likely to cause segregation, and manganese and sulfur have the same effect to a less marked extent. Segregation is not commonly encountered in iron founding, however, since other considerations usually require a degree of freedom from excessive amounts of phosphorus, sulfur, or manganese which will minimize the danger of segregation.

Chilling. The intentional chilling of iron by the insertion of metal chills in a mold has been discussed in Art. 162. The production of properly chilled iron is a very difficult problem, mainly on account of the effect of variations in composition of the iron upon the depth of chill obtained. The most important factors in this regard are the contents of silicon and of sulfur. If the silicon is comparatively high and the sulfur very low, chilling is practically impossible. If both silicon and sulfur are very low, a considerable amount of chill is obtained, and the best results are obtained when a low percentage of silicon is combined with a rather high percentage of sulfur. Phosphorus has little effect upon the depth of chill. Manganese increases the hardness of the chilled iron.

175. Hardness. The principal factor in determining the hardness of cast iron is the amount of combined carbon. This is due, first, to the hardness of cementite itself, and second, to the fact that increase in combined carbon usually means a decrease in graphite carbon, which is very soft. Graphite has a further effect in increasing the ease with which cast iron may be worked.

The influence of elements other than carbon upon the hardness of iron is, with the exception of manganese, directly dependent upon their power to vary the amount of combined carbon. Silicon, therefore, acts as a softener, unless its percentage exceeds about 3 per cent, when the effect is reversed. Sulfur and phosphorus act as hardeners in all percentages, and manganese, in addition to its indirect effect on combined carbon, has a direct hardening influence owing to the hardness of the compound $(FeMn)_3C$.

176. Tensile Strength. The tensile strength of cast iron is dependent upon the founding methods, the design, and the size of castings. In addition, the composition, and more particularly the constitution, exert a great influence upon strength.

The presence of graphite plates in any proportion must necessarily decrease the strength of the iron as a whole. This injurious effect of graphite is not necessarily directly proportional to the degree of continuity of the graphite mesh.

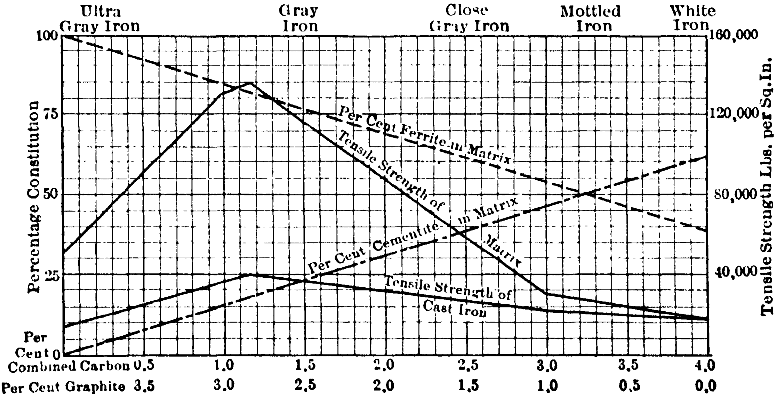

Fig. 60.—Approximate Relationship Between Tensile Strength of Cast Iron and State of Carbon. (Howe.)

Any diminution in the proportion of graphite will, in general, diminish in some degree the continuity of the graphite mesh and will, therefore, lessen its detrimental effect upon strength. This increase in the proportion of cementite in the matrix means a proportionate increase in its strength until the percentage of cementite in the iron reaches a certain point, which is in the neighborhood of 1.2 per cent for an iron containing about 4 per cent total carbon. Further increases in the percentage of cementite beyond this point increase hardness and brittleness at the expense of toughness, ductility, and strength. It is evident, therefore, that the strength of an iron will be greater when the percentage of combined carbon does not exceed about 1.2 per cent than it will be if any higher percentage is present. Whether the highest strength is found with about 1.2

per cent cementite or when the percentage of cementite is below this point will depend upon whether the loss of strength due to increase in graphite, on the one hand, or the gain in strength due to the higher carburization of the steel matrix, on the other hand, is the more influential factor.

The approximate relation between tensile strength and state of carbon is shown graphically by the diagram of Fig. 60, which is abstracted from the original of Professor Henry M. Howe. In this diagram it has been assumed that the iron possesses a constant total carbon content (4 per cent).

177. Influence of Metalloids and Rate of Cooling upon Strength. The influence of the metalloids and the rate of cooling upon the strength of castings is largely an indirect one, dependent upon the extent to which the separation of graphite is facilitated or retarded.

Silicon in small amounts, by favoring the precipitation of graphite, exerts an influence which is beneficial to strength, provided that an excessive amount of combined carbon would otherwise be present. In this event the gain in strength of the matrix which accompanies the relief of brittleness more than compensates for the injurious effect of the increase of graphitic carbon. If, on the other hand, the additional graphite precipitation caused by silicon produces an iron whose matrix possesses too little combined carbon, the iron is weakened both because of the lowering of the strength of the matrix and because of the weakening and softening influence of the graphite.

The influence of sulfur, when present as FeS, is always as a weakener of cast iron, not only because it prevents the separation of graphite chemically and by hastening solidification, but also because it promotes the inclusion of flaws (blowholes, sandholes, or shrinkage cracks), induces internal stresses, and causes coarse crystallization and brittleness. The harmful influence of sulfur may, of course, be more or less completely neutralized by much larger percentages of silicon or by the presence of about twice as much manganese.

Phosphorus usually tends to weaken cast iron. When the silicon is high, however, a moderate amount of phosphorus may, by increasing the time of solidification, promote the separation of graphite as above explained, thereby improving strength. The presence of more than about 0.05 per cent phosphorus will, however, always be detrimental to strength.

The effect of manganese upon strength is always dependent upon the relative amounts of sulfur and manganese present. If the manganese content does not exceed twice the sulfur content, the manganese simply neutralizes the tendency of sulfur to decrease the proportion of graphite, and therefore the manganese increases strength. When the content of manganese exceeds the amount required to neutralize the sulfur, however, the excess manganese has a marked effect detrimental to strength because of the resultant excessive increase in the proportion of combined carbon.

178. Stress-strain Diagram for Cast Iron. Cast iron exhibits a great variation in elastic properties, since so many factors affect its strength.

In Fig. 61 typical stress-strain diagrams for three radically different cast irons are presented in order to illustrate their usual behavior under tensile stress.

It will be observed that there is no well-defined elastic limit or yield point. For the typical irons shown, the ultimate strength falls at 35,500 pounds per square inch for the hard gray iron, 22,500 pounds per square inch for the average gray iron, and 16,000 pounds per square inch for the soft gray iron.

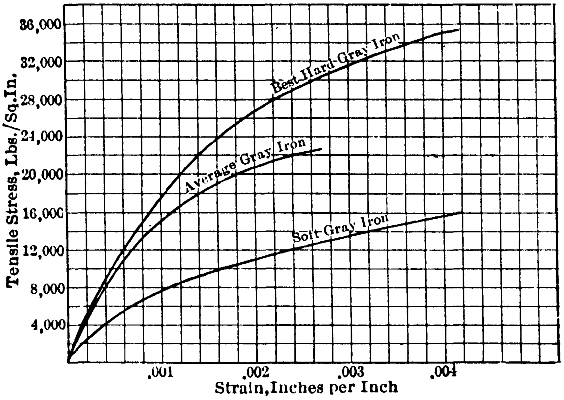

FIG. 61.—Stress-strain Diagrams for Cast Irons. (Tension.)

No constant proportionality of stress to strain exists for any considerable load interval, and therefore the modulus of elasticity must be determined by an arbitrary method. The value of *E* as determined by the initial tangent method is about 30,000,000 pounds per square inch for hard cast iron, 24,000,000 pounds per square inch for average iron, and 14,000,000 pounds per square inch for soft iron. The values of *E* as determined by the tangent method at 5000-pounds-per-square-inch stress have decreased to about 20,000,000 pounds per square inch, 15,000,000 pounds per square inch, and 7,000,000 pounds per square inch, respectively; and at 10,000-pounds-per-square-inch stress, the values of *E* are about 15,000,000 pounds per square inch for hard iron and about 14,000,000 pounds per square inch for average iron.

The percentage elongation is small for all cast irons, rarely exceeding from 3 to 4 per cent for any grade, and the reduction of area is usually too slight to be appreciable.

179. Compressive Strength. The compressive strength of cast iron, as for all comparatively brittle materials, is largely a function of the shearing strength, since failure occurs along an oblique plane unless the specimen tested is sufficiently long to permit failure by lateral flexure.

The factors which control compressive strength are exactly the same as those which control tensile strength. The most important consideration, therefore, is the state assumed by the carbon, and compressive strength will be benefited by all agencies which tend to increase the proportion of graphite carbon and decrease combined carbon, until the point of saturation of carbon in the steel matrix is reached (about 1.2 per cent combined carbon), beyond which point further increases in graphite mean a loss in strength of the matrix, and therefore a loss in strength of the iron as a whole.

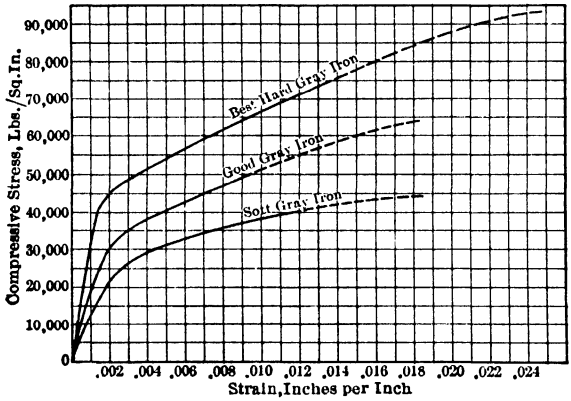

Fig. 62.—Stress-strain Diagrams for Cast Irons. (Compression.)

Compressive tests of cast iron show very wide variation in strength. If large specimens such as structural columns are tested, the ultimate strength will seldom be found to exceed 30,000 to 40,000 pounds per square inch. If, however, short specimens of small size are tested, the strength will be found to run to 50,000 to 125,000 pounds per square inch.

Three typical stress-strain diagrams for compression of short blocks of cast iron are presented in Fig. 62. It will be observed that the yield point is much more clearly marked in compressive tests of cast iron than in tensile tests, although no absolutely constant ratio of stress to strain is maintained for any considerable load interval.

The ultimate strengths of the three irons are 93,000 pounds per square inch, 63,000 pounds per square inch, and 44,000 pounds per square inch. for hard, average, and soft irons, respectively. The moduli of elasticity as determined by the tangent method at a stress of 10,000 pounds per square inch are about 30,000,000 pounds per square inch, 20,000,000 pounds per square inch, and 12,000,000 pounds per square inch, for the three classes of iron, while at 20,000-pounds-per-square-inch stress the value of E has dropped to about 25,000,000 pounds per square inch, 16,000,000 pounds per square inch, and 8,000,000 pounds per square inch, respectively.

180. Transverse Strength. The transverse or flexural strength of cast iron is very valuable as the criterion by which the quality of the material going into gray iron castings may be judged. Transverse strength is affected by the same factors as tensile strength, since failure under transverse loading is really failure by tension on the tension side of the beam. Three sizes of cylindrical transverse test bars are commonly employed (Table XI).

TABLE XI

A.S.T.M. Requirements for Cast Irons

Controlling Section of Casting		0.50 in. and under	0.51 to 1.00 in.	1.01 to 2.00 in. (and over)
Transverse test bar		A	B	C
Diameter of transverse test bar, in.		0.875	1.20	2.00
Span length, in.		12	18	24
Length of bar, in.		15	21	27
Class No.	Tensile Strength, Min., lb. per sq. in.	Breaking Load at Center, lb.	Breaking Load at Center, lb.	Breaking Load at Center, lb.
20	20,000	900	1800	6,000
25	25,000	1025	2000	6,800
30	30,000	1150	2200	7,600
35	35,000	1275	2400	8,300
40	40,000	1400	2600	9,100
50	50,000	1675	3000	10,300
60	60,000	1925	3400	....

181. Specifications for Gray Cast Iron. The specifications of the American Society for Testing Materials classify gray cast irons with respect to tensile strength into seven classes, Nos. 20, 25, 30, 35, 40, 50, and 60, as shown in Table XI. Each class corresponds to the minimum tensile strength required in thousands of pounds per square inch. The tension-test specimens are machined from test bars which are cast separately from the casting. The requirements of transverse strength for these classes of irons are also given in Table XI.

Classes 20, 25, and 30 cover the ordinary grades of gray cast iron. Classes 35, 40, 50, and 60 are considered to be high-strength irons, particularly in medium and heavy sections. Since, in general, the higher-strength irons are more difficult to produce in heavy sections, and more difficult to machine, the specification of a stronger cast iron than is needed may result in unnecessarily increased costs in producing the casting and in machining.

In addition to the above requirements, special tests are sometimes specified for cast-iron products, such as the drop test for car wheels, the chill tests for locomotive cylinders and car wheels, or the hydrostatic pressure tests for pipe.

182. High-strength Cast Iron. Cast irons of classes 35, 40, 50, and 60 are usually produced by the addition of steel to the iron, thus decreasing the percentages of carbon and silicon and consequently increasing the strength through reducing the formation of graphite. Such iron can be produced without the addition of alloys, but requires careful control of melting, molding, and pouring. The high-strength cast irons are harder and more difficult to machine, requiring the use of cemented carbide tools with much coolant solution.

183. Heat Treatment of Gray Cast Iron. The tensile strength and hardness of gray cast iron can be increased by quenching in oil from about 871° C. (1600° F.) and tempering at about 427° C. (800° F.). If the iron is quenched only and not tempered, the metal will be under such internal strain that the tensile strength will be reduced, but, if the heat treatment is properly conducted, an increase of about 10 per cent will be obtained. Hardening and tempering are particularly beneficial to iron with a total carbon content of 3 per cent or less; the silicon content should not exceed 2 per cent. A cast iron so treated is extremely wear resistant and can be used for cams, dies, and other parts subjected to wear.

The machinability of high-strength cast iron can be greatly improved by tempering conducted at a temperature below 705° C. (1300° F.) to soften the matrix of iron. Hardness can be reduced from 300 to 240 Brinell with only a moderate reduction in tensile strength. In general, the higher the temperature of tempering and the longer the heat treatment, the more the tendency for carbon combined in cementite to go to the graphitic form, thus reducing the tensile strength and hardness.

Careful control and good technique are required to obtain good results in heat-treating cast iron, for two reasons: (1) cast iron has a higher critical temperature than steel because of its higher silicon content (871° C. [1600° F.] is usually adequate); and (2) cast iron has a high carbon content. Castings must be allowed to soak sufficiently to reach a uniform temperature throughout. In hardening, castings must be quenched quickly before the surfaces can cool during removal and handling. Surface layers which have been air cooled will not harden even though the core may reach a satisfactory hardness. In order to prevent decarburization of the graphite exposed on the surfaces of the castings during heat treatment, the atmosphere should be controlled artificially, preferably by packing the castings in carburizing boxes with partly spent carburizing compounds or with cast-iron borings.

Heat-treated cast iron expands during the hardening process. This growth can be diminished by first annealing the castings by heating at 732° C. (1350° F.) for about 4 hours. After annealing, the castings can be machined with great ease and the heat treatment will cause a much smaller amount of growth and distortion.

184. Alloy Cast Irons. Nickel, chromium, or a combination of nickel and chromium is often used with beneficial effect in the preparation of so-called "alloy" cast irons. The effect of these alloying elements is somewhat variable, depending on the percentages of the other elements present, and particularly on the proportions of graphite and combined carbon.

In general, the effect of nickel is to harden the iron, and thereby increase its resistance to wear, without materially decreasing its machinability. The resilience of cast iron is also improved and considerable grain refinement is caused by addition of nickel.

The addition of 0.5 to 1.0 per cent of chromium counteracts the tendency for combined carbon to be changed to graphite during heat treatment. Chromium carbide is formed, which is very stable. Such alloy iron can be heat-treated into an extremely tough, high-strength material by holding at about 705° C. (1300° F.) for a period of time. This treatment converts the pearlite in the cast matrix into a mixture of ferrite and cementite particles in a manner similar to the spheroidizing of tool steel for the purpose of increasing toughness and improving machinability. The resultant iron has high strength, excellent toughness, and some ductility; it is easily machined and has good wear resistance. For small lots of castings this process may be more economical than quenching and tempering unalloyed gray-iron castings.

If chromium and nickel are used in proper proportions (1 to 2 parts nickel to 1 part chromium), and if the percentages of carbon, silicon, and phosphorus are carefully controlled, a casting will result which, in addition to good grain refinement, high strength, and hardness, will be uniform, even in heavy sections, and will also show excellent machining qualities and resistance to wear.

Nickel is added either in the cupola charge or in the ladle, generally in amounts between 2 and 5 per cent. Irons containing both chromium and nickel may be prepared by using Mayari pig iron in the charge. This pig iron is smelted from Cuban ores containing chromium and nickel and is used extensively in the preparation of Mayari steel (Art. 253).

The alloy cast irons are used in the manufacture of chilled rolls, chilled car wheels, grinding machinery, sand-blast nozzles, rolling-mill guides, engine cylinders, pistons, etc.

QUESTIONS

1. Describe the cupola and the air-furnace methods of manufacturing cast iron, and state the advantages of each method.

2. Describe the essential steps in iron founding.

3. In what state is the carbon in gray cast iron; in white cast iron?

4. Sketch the microstructure of gray cast iron; of white cast iron.

5. Briefly discuss the effects of carbon, silicon, phosphorus, sulfur, and manganese on the properties of cast iron.

6. Discuss the relationship between tensile strength and the state of carbon in cast iron.

7. Give typical values of the ultimate tensile strength, ultimate compressive strength, and modulus of elasticity in tension of commercial gray cast iron of a good grade.

8. Describe the heat treatment of gray cast iron.

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CHAPTER IX

MALLEABLE CAST IRON

185. General. Malleable cast iron is iron of special composition which, after having been cast or rolled to its final form, is rendered malleable by a process of annealing. It is essential that the iron used be a white iron before malleablizing, in order that the carbon may be almost wholly in the combined form. The malleablizing process will then result in the conversion of the combined carbon into free carbon in an amorphous condition, not resembling free carbon in the crystalline form as graphite. This amorphous carbon will exist as isolated particles in a continuous mesh of metal. Through this circumstance the casting is rendered very much tougher than white or gray cast iron, and its ductility and malleability are increased to such an extent that it may be bent or twisted to a considerable degree even when cold.

Malleable iron combines the advantages of ordinary cast iron, with respect to the ease with which complicated forms may be cast, with a considerable degree of toughness, ductility, and strength. Its physical properties approach those of mild carbon-steel castings, and from the standpoints of uniformity, soundness, and machinability it surpasses steel.

The uses for which malleable castings are especially adapted are very numerous. This material is especially valuable in the manufacture of that large class of articles whose form is too complicated for economical forging, but which must possess a strength and toughness not attainable in gray castings.

Among the more common applications of malleable iron may be especially mentioned its use on railroad work. Couplers are commonly made of malleable iron, as are the journal boxes, brake fittings, and many other small fittings for rolling stock. Other uses include many agricultural implements and parts of agricultural machinery, all manner of pipe fittings, elbows, unions, valves, etc., household and harness hardware such as parts of locks, hinges, window and door fittings, buckles, and swivels.

Another class of articles is made of malleable iron that has been casehardened after prolonged annealing. The material then closely resembles cast steel, and is often sold as such. These articles include many carpenter tools, such as hammers, hatchets, chisels, and planer irons, also pistol parts, skates, shears, etc.

MANUFACTURE OF MALLEABLE CASTINGS

186. The Materials Used. The charge of the furnace of a malleable-iron foundry includes pig iron, sprues, annealed malleable-iron scrap, and steel scrap.

The pig iron should contain not more than 0.60 per cent manganese, not more than 0.225 per cent phosphorus, not more than 0.05 per cent sulfur, and not less than 2.75 per cent total carbon. The silicon requirement varies according to the castings made. Heavy castings require from 0.75 to 1.50 per cent silicon; light castings, from 1.26 to 2.00 per cent.

The sprues or "hard scrap" include the gates and scrap castings that have not been annealed. Thorough cleaning of the sprues to remove the burned sand is very necessary.

Malleable scrap is difficult to melt because of the comparative infusibility of the skin of malleable castings. It contributes greatly to the strength of the castings made, however, and if the large scrap is broken up before charging, it may be handled without serious difficulty.

Steel scrap of any sort may be used as a part of the charge with beneficial results, if added after the balance of the bath is molten.

187. Melting Malleable-iron Mixtures. Three types of furnaces are used in melting iron for malleable casting: the cupola, the air furnace, and the open-hearth furnace. The cupola process for melting iron for malleable-iron castings differs in no respect from ordinary gray-iron foundry practice, except in the higher proportion of fuel charged. The advantages of the cupola process lie in the cheapness of installation and operation, the comparative ease with which the furnace is controlled, and the small loss of silicon in melting. The disadvantages are the great danger of burning, owing to the direct contact of metal and fuel, and the extremely close structure of the hard castings produced, which causes trouble in annealing. Very little malleable scrap, and no steel, can be used in the cupola.

The advantages of the air furnace as compared with the cupola are principally the better grade of castings produced, the wider range of scrap material possible, the shorter time required for pouring, the less serious consequences of a breakdown, and the better control over process and product. The disadvantages of the air-furnace process are the greater expense of equipment, the greater skill required in operation, and the longer time for melting.

The open-hearth furnace is operated in the malleable-iron foundry in almost exactly the same manner as in the production of open-hearth steel. Its advantages over the air furnace are the saving of time required for melting, the very exact control of the process, and the resultant high efficiency and gain in the percentage of first-grade castings. The disadvantages are the high cost of installation, the heavy repair bill, the necessity of having gas fuel, and the necessity of continuous operation.

188. Foundry Methods for Malleable Castings. Molds for malleable castings are made in the same manner as gray-iron castings in green sand.

Particular care must be exercised to furnish proper gating in handling white-iron mixtures, and risers or feeders must be provided where thin sections are encountered, to prevent cooling of the metal at these points before the mold is completely filled.

Chills are very commonly used in molds for malleable castings, particularly for the sake of cooling the larger parts of castings rapidly, thereby preventing the possibility of graphite separating out, as it tends to do with slow cooling.

Molten white iron is a very different material from molten gray iron. The former must be poured very hot, and as rapidly as possible, to insure proper complete filling of the mold. Iron that has chilled slightly, or that has been burned in the furnace, will be sluggish, and must not be poured except in pig-beds for use in subsequent heats.

Hard castings for malleable iron are cleaned by any of the methods common to the gray-iron foundry. Very careful inspection of the cleaned castings is necessary, and all defective castings are rejected before being annealed. The gates are also chipped off and the castings are separated into a number of classes.

189. Graphitization by Heat Treating. The castings are graphitized or malleablized by means of a suitable heat treatment which converts the hard white iron into a ductile, strong, tough, and easily machinable product. The treatment consists of heating to a temperature above the critical point, maintaining this malleablizing temperature, cooling to the critical point, maintaining at a temperature slightly below the critical point, and finally cooling to room temperature.

White cast iron consists of pearlite and cementite; its structure is illustrated in the photomicrograph of Fig. 63. Heating to a point just above the critical temperature (about 760° C. [1400° F.] for iron of usual silicon content) transforms the pearlite into austenite, the cementite remaining unchanged. Austenite is a constituent of indefinite composition with respect to carbon, capable of dissolving carbon in amounts proportional to its temperature. Accordingly, when in the process the temperature is raised to about 871° C. (1600° F.), the austenite absorbs as much carbon from the cementite as it can hold at that temperature. As the temperature is maintained, the austenite gives up some of the absorbed carbon which is precipitated in the form of "temper" carbon. As this precipitation takes place, the austenite absorbs more carbon from the cementite until all the carbon in the cementite has been dissolved. At this stage some carbon has been precipitated and the remainder is in the austenite. Then the temperature is slowly lowered to the critical temperature and more temper carbon is precipitated from the austenite. At the critical temperature, however, the austenite still contains the amount of carbon originally present in the pearlite of the white iron. To prevent reversion to the relatively hard pearlite in passing through the critical temperature, and to effect complete precipitation of the carbon, it is slowly cooled to about 590° C. (1275° F.), where the temperature is maintained to permit the breaking up of the austenite into ferrite and temper carbon.

In brief, the malleablizing process converts hard, brittle white cast iron with a structure of pearlite and cementite into malleable cast iron with a structure of relatively soft ferrite and carbon in the free amorphous form called "temper" carbon. This structure is shown in the photomicrograph of Fig. 64.


FIG. 63.—White Cast Iron 100×.

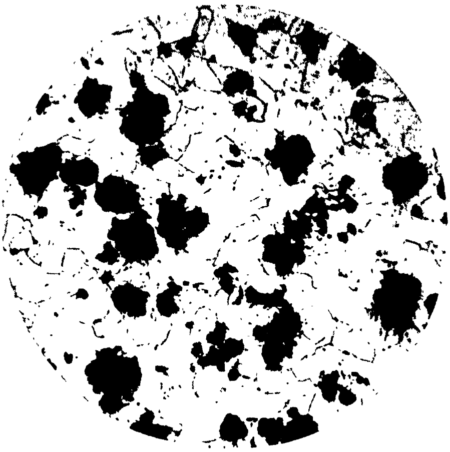
FIG. 64.—Malleable Cast Iron 100×.

In order to prevent oxidation during the process, and also warping of the castings, the castings must be packed in annealing pots surrounded by a proper packing material. This packing material might be sand, clay, or other inert material, and the heat alone would effect the desired change in the state of the carbon and produce malleable castings. Higher-grade and stronger castings are produced, however, when the packing material is a decarbonizing agent such as iron oxide. This results in the migration of carbon from the outer shell of the casting, producing a layer resembling steel about $\frac{1}{16}$ inch thick, encased in a skin of almost carbonless iron on the surface. This skin may subsequently be enriched in carbon by a case-hardening process, and, if the reduction of carbon has previously been carried to the maximum depth possible (about $\frac{1}{4}$ inch), the resultant material will greatly resemble cast steel. It may even be hardened and tempered.

The packing material used is commonly the cinder or slag squeezed from the wrought-iron puddle balls. This slag is a very rich iron oxide high in silica. Hematite ore in a pulverized state is also suitable for a packing material, especially for cupola iron the annealing temperature of which is sufficient to cause puddle cinder to cake together and fuse on to the castings. Rolling-mill scale is also used, and magnetite has been found very satisfactory. If sand has not been perfectly removed from the castings, it causes trouble by combining with the oxide of the packing material, increasing its fusibility and causing the castings and packing to bake together.

When one pot has been filled, another pot is superimposed on it and filled in a similar manner. Several pots in such a stack constitute what is known as a stand. The top of the stand is covered with flat cast-iron pieces and sealed with clay to prevent the access of oven gases to the castings.

190. Types of Malleablizing Furnace. Malleablizing or annealing furnaces are of either the periodic or continuous types. The periodic type predominates in general usage; this type of oven is ordinarily of rectangular box form with a fire pot at one end on the outside, the products of combustion passing from it to the oven proper over a communicating bridge wall. It may be heated with powdered coal, oil, gas, or electricity, though the first two are most generally used because of their lower cost. The regenerative principle is not employed in this type of oven, since the castings must cool slowly in the oven itself. The capacity varies from about 25 to 45 tons of castings charged, and the total time for the process averages about 7 days.

The muffle oven, which is also of periodic type, consists of an insulated rectangular brick shell supported on the outside by steel plates and buck stays. Within this shell, a firebrick muffle is constructed with a space between it and the brick shell sufficient for proper combustion of the fuel, and so arranged with flues as to enable the flame to heat the entire surface of the muffle. In most such ovens oil or natural gas is the fuel. Since the products of combustion do not come in direct contact with the castings, the necessity of packing the castings in pots is avoided.

Tunnel kilns of the continuous type vary from 200 to 350 feet in length. The stands are loaded on short cars which when in the kiln form its bottom. The cars on passing through the tunnel are subjected to a gradation of temperature so timed as to correspond to the heating cycle required. In the continuous kiln the malleablizing time is shortened about 2 days.

191. Malleablizing Period. The complete malleablizing or annealing cycle may be subdivided into five distinct intervals. First, the temperature is slowly increased in about 2 days' time to about 871° C. (1600° F.); second, this annealing temperature is maintained for 48 to 60 hours; third, the castings are slowly cooled to the critical temperature and are held just under the critical point for about 35 hours, after which they are cooled to permit handling. About 6 days are required.

The annealed castings must be cleaned to remove the scale which has formed. This is accomplished in tumbling barrels.

In order to test the quality of the annealed iron, "test plugs," which are simply small projections, about ¾ by ½ by 1 inch long, are cast on the more important work. These are broken off and the fracture examined. If normal, the fracture should have a black velvety surface in the interior, surrounded by a band of dark gray about $\frac{1}{16}$ inch thick, and this in turn should be encased in a band of white not more than $\frac{1}{64}$ inch thick.

192. Types of Malleable Cast Iron. There are two types of malleable cast iron, namely, black-heart and white-heart. *Black-heart* malleable iron, so called because a fractured surface has a black appearance, is usually produced in American practice. The descriptions in this chapter pertain to black-heart iron. *White-heart* malleable iron is usually produced in European foundries; the process requires the maintenance of a higher annealing temperature for a longer time, the effect of which is not only to break down the combined carbon (Fe_3C) into temper carbon and ferrite, but also to decarburize the iron very markedly, producing a white heart of nearly pure iron.

PROPERTIES OF MALLEABLE-IRON CASTINGS

193. Chemical Composition and Constitution. The percentage composition of malleable cast iron may vary considerably depending upon the properties desired, especially tensile strength. Also, carbon at the center of a thick section may be nearly the initial total carbon while very thin sections may be almost completely decarburized. The following tabulation presents average values of chemical composition of good malleable iron:

	Per Cent
Carbon	1.00 to 2.00
Silicon	0.60 to 1.10
Manganese	under 0.30
Phosphorus	under 0.20
Sulfur	0.06 to 0.15 (usually about 0.10)

Since there is no combined carbon in malleable cast iron, phosphorus may be present up to 0.20 per cent without danger of cold shortness. A sulfur content as indicated is not objectionable since malleable cast iron is not hot-worked.

The constitution of malleable iron is extremely variable, even in a single casting, because the effect of the annealing process is largely dependent upon the thickness of the casting. The outermost skin is practically carbonless iron. The intermediate gray portion of black-heart malleable castings consists largely of ferrite, but contains scattered particles of free carbon in the amorphous state, called temper carbon. The black interior consists of ferrite in which many isolated particles of temper carbon are interspersed. White-heart malleable castings have the constitution of the intermediate portion of black-heart castings for the most part, but the outermost band of practically pure ferrite is much thicker in the former than in the latter.

194. Physical Properties. The average physical properties of American malleable cast irons are as follows:

Tensile strength	54,000 lb. per sq. in.
Yield point	36,000 lb. per sq. in.
Elongation in 2 in.	18 per cent
Modulus of elasticity in tension	25,000,000 lb. per sq. in.
Brinell hardness number	115; range, 100–140
Izod impact value	9.3 ft-lb.
Charpy impact value	7.75 ft-lb.
Fatigue endurance limit	25,000 lb. per sq. in.
Ultimate shearing strength	48,000 lb. per sq. in.
Yield point in shear	23,000 lb. per sq. in.
Specific gravity	7.15 to 7.45
Average coefficient of thermal expansion	0.0000066 per degree F.

The specifications of the American Society for Testing Materials for two grades of malleable iron castings, Nos. 32510 and 35018, require minimum tensile strengths of 50,000 and 53,000 pounds per square inch, minimum yield points of 32,500 and 35,000 pounds per square inch, and minimum elongations in 2 inches of 10 and 18 per cent, respectively.

195. Pearlitic Malleable Cast Iron. Pearlitic malleable cast iron contains both temper carbon and combined carbon. The matrix containing cementite can vary in a manner similar to steel from almost a completely ferritic structure to an almost completely pearlitic structure. The combined carbon can be in the form of pearlite or in the form of martensite, troostite, sorbite, and, under certain conditions, austenite. Tensile strength will range from 54,000 pounds per square inch for ordinary malleable iron to 120,000 pounds per square inch for martensitic "pearlitic malleable" iron. The ductility is similar to that of cast steel but somewhat lower owing to the presence of temper carbon.

Pearlitic malleable cast iron is produced by two processes. In the first the castings are completely malleablized and afterwards are reheated above the critical temperature to redissolve a portion of the temper carbon as combined carbon. This cementite is retained by rapid cooling with the formation of a pearlitic matrix. In the second process the castings are incompletely malleablized so that the castings as cooled contain both temper carbon and combined carbon which has never been decomposed. In this process two variations are possible: (*a*) white iron of normal analysis is used but is incompletely malleablized, and (*b*) white iron is used of an analysis which will not completely malleablize under normal conditions. Pearlitic malleable cast iron produced by the above methods may be heat-treated to produce martensitic, troostitic, or sorbitic structures.

196. Rolling White Cast Iron. Under certain conditions of control it is possible to roll white cast iron completely to the desired shape as white iron, which subsequently can be malleablized to precipitate temper carbon and form malleable iron or "pearlitic malleable" iron. By controlling the analysis of the white iron, the metal can be rolled to shape and at the same time the formation of temper carbon can be almost completed. Only a short heat treatment is then required to bring the structure of the matrix to the desired form. The temper carbon particles are greatly elongated by rolling; the fracture resembles the fibrous fracture of wrought iron, the elongated particles of temper carbon acting similarly to the elongated slag fibers in wrought iron.

QUESTIONS

1. Describe the materials and methods used in producing white-iron castings.
2. Describe the malleablizing process.
3. Sketch the microstructure of malleable cast iron, labeling each constituent.
4. How is decarburization accomplished?
5. Distinguish between black-heart and white-heart malleable iron.
6. State average values of the chemical composition of a good grade of malleable cast iron.
7. Discuss the physical properties of malleable cast iron.
8. Name typical articles manufactured from malleable cast iron.
9. What is pearlitic malleable iron? How may it be produced?

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CHAPTER X

NON-FERROUS METALS AND ALLOYS

THE PURE METALS

197. The Non-ferrous Metals of Industrial Importance. The non-ferrous metals of greatest industrial importance comprise aluminum, copper, lead, magnesium, nickel, tin, and zinc. Those of secondary importance include antimony, bismuth, cadmium, and mercury. A number of these latter metals are chiefly important as alloy elements, and others, such as chromium, cobalt, molybdenum, titanium, tungsten, and vanadium, are used largely as alloy metals.

The non-ferrous alloys of greatest importance are the alloys of copper with tin, *the bronzes,* the alloys of copper with zinc, *the brasses,* the alloys of aluminum, and those of nickel. Many important special bronzes and brasses are made, however, in which a third alloy element is included. For this purpose tin or zinc, lead, phosphorus, manganese, aluminum, silicon, iron, titanium, and vanadium are most common.

Aside from the bronzes and brasses, copper forms more or less valuable alloys with practically all the metals listed above; aluminum is the principal metal of a number of important alloys, and the same is true of zinc, lead, tin, nickel, and a few others.

The principal non-ferrous metals and alloys are listed in the classification which follows:

CLASSIFICATION OF NON-FERROUS METALS AND ALLOYS

NON-FERROUS METALS

Metals of Primary Importance
- Copper
- Zinc
- Lead
- Tin
- Aluminum
- Magnesium
- Nickel

Metals of Secondary Importance
- Bismuth
- Antimony
- Cadmium
- Mercury
- Silver
- Gold
- Platinum

Metals Chiefly Important as Alloy Elements
- Chromium
- Cobalt
- Vanadium
- Tungsten
- Molybdenum
- Titanium
- Uranium
- Zirconium

NON-FERROUS ALLOYS

Ordinary Bronzes. Copper-tin Alloys.		
Special Bronzes. Copper-tin	Zinc Lead Phosphorus Manganese Silicon Aluminum Vanadium Nickel Titanium	Alloys
Ordinary Brasses. Copper-zinc Alloys.		
Special Brasses. Copper-zinc	Lead Aluminum Manganese Iron Vanadium Phosphorus Silicon	Alloys
Other Binary Alloys of Copper. Copper	Aluminum Nickel Manganese Phosphorus Silicon Vanadium Chromium Tungsten Antimony Bismuth Lead Arsenic	Alloys
Alloys of Zinc. Zinc	Lead Tin Antimony Bismuth Aluminum-copper	Alloys
Alloys of Lead. Lead	Tin Antimony Bismuth Cadmium Arsenic Barium	Alloys
Alloys of Tin. Tin	Cadmium Antimony Bismuth Nickel Zinc-lead	Alloys
Alloys of Aluminum. Aluminum	Copper Silicon Silicon-copper Copper-magnesium Magnesium Zinc Copper-zinc Copper-manganese Nickel Tin Manganese Tungsten Chromium Titanium	Alloys

NON-FERROUS ALLOYS—*Continued*

Alloys of Magnesium. Magnesium	Aluminum Zinc Copper	Alloys
Alloys of Nickel. Nickel	Copper Aluminum Chromium-iron Zinc-copper	Alloys
Die-casting Metals	Zinc-aluminum Aluminum-silicon Aluminum-silicon-copper Magnesium-aluminum Copper-zinc	Alloys
Special Bearing Metals	Bronzes (Ordinary and Special) Copper-lead Lead-antimony Tin-copper-antimony Lead-tin-antimony Lead-copper-antimony Zinc-tin-antimony Lead-tin-bismuth Lead-barium Lead-calcium	Alloys

Space cannot be devoted to a detailed consideration of all the metals and alloys listed above. A brief treatment of the metallurgy, properties, and uses of the more important ones will be presented, supplemented by a few general statements concerning those of less importance.

COPPER

198. Classification of Commercial Forms of Copper. Ores of copper are found in almost every important country of the world, and native copper is found in the region abutting upon the south shore of Lake Superior, and in a few other localities. Copper ores exist in a great variety of forms, usually as sulfide or oxide. The greater proportion of the world's supply of copper is derived from copper pyrites.

The classification of copper most common in the United States is not a particularly rational one, but one which trade conditions have imposed. The American Society for Testing Materials recognizes three general classes of American copper, which may be defined as follows:

Electrolytic copper is copper derived by the electrolysis of a copper sulfate solution with anodes of crude copper and cathodes of pure copper. (Copper migrates from the anode, leaving its impurities behind, and is deposited on the cathode.)

Lake copper is copper that has originated on the northern peninsula of Michigan, U. S. A.

Casting copper is more or less impure copper that is either fire-refined copper from virgin sources, copper electrolytically produced by deposition from impure liquors, or copper reclaimed from secondary sources.

Electrolytic copper has largely replaced all other classes whenever a pure grade of copper is demanded. A large proportion of the electrolytic copper produced is derived from copper pyrites and has previously been smelted and fire-refined. The process of electrolysis results in the recovery of practically all the precious metals commonly present in copper ores, and since this gain, as well as the added market value of electrolytically refined copper, will usually pay the extra cost of electrolytic refining, the amount of casting copper produced is in consequence relatively very small. A considerable portion of even the lake copper is electrolytically refined, either to free it from impurities or to recover the silver content.

Special types such as argentiferous copper, arsenical copper, oxygen-free copper, and phosphor-deoxidized copper are produced in limited quantities for particular service requirements, which may include one or more of the following: increased softening temperature, resistance to exposure at elevated temperatures, and ease of soldering and of welding. The use of these special coppers is warranted only where a definite advantage is obtained.

199. The Extraction of Copper from Its Ores. The metallurgy of copper is very complex on account of the great variety of the ores and the frequent necessity of providing for the recovery of not only copper, but also the precious metals which occur in copper ores. The number of metallurgical methods of extraction of metallic copper is therefore very large.

The chief sources of copper are ores which are essentially more or less complex sulfides, ores which, although originally sulfides, have by atmospheric agencies been altered to oxides and carbonates, and native copper ores wherein the copper exists as free metal.

Sulfides ores are usually treated by one of the following three general processes: (*A*) Roasting, smelting, and converting; (*B*) pyrite smelting; and (*C*) alternate oxidation and reduction. When the ores are wholly oxidized the copper may be recovered by a process of direct reduction.

Roasting, Smelting, and Converting. Roasting has for its principal objects the burning of the sulfur contents of the ore to sulfur dioxide (SO_2), which passes away as gas, and the changing of the metal with which the sulfur was combined into an oxide. No effort is made, however, to eliminate the sulfur entirely, or completely oxidize the metal, since some sulfur and lower oxides are desirable in the subsequent smelting operation.

Two types of furnaces are in use, the reverberatory and shelf furnaces. Finely crushed ore is roasted in reverberatory furnaces similar to those for smelting. The shelf furnace contains six circular hearths, one above the other, provided with openings alternately at the center and at the periphery to permit the descent of the ores. A vertical hollow shaft traverses the center of the furnace, carrying rabbles which are set to move the material toward the outlet opening of each hearth. The air required for combustion is forced in by a fan at the bottom, and the products of combustion (principally sulfur dioxide gas) escape through a flue provided at the top. The ore is delivered by hoppers to a drying hearth on the top of the furnace; rabbles gradually transfer it to the peripheral opening leading to the top roasting hearth, and by the motion of successive sets of rabbles it is gradually dropped from hearth to hearth, falling alternately at the center and the periphery, until it leaves the lowest hearth in a roasted condition. After a cold furnace has been brought to temperature and the ores have reached a dull red heat, calcination thereafter continues by the combustion of the sulfur of the ore without any extraneous fuel.

Smelting of copper ores has for its object simply the concentration of the ore by removal of the earthy portion or gangue, in order that only the metallic portion may have to be treated by the subsequent more expensive refining process. Copper ores are smelted either in a blast furnace or in a reverberatory furnace. The ultimate product of the smelting operation is a large amount of slag and a small metallic portion called *matte*, which is essentially a mixture of metallic sulfides of copper, iron, and other metals originally present in the ore.

The matte is converted into metallic copper in a Bessemer converter of side-blown type with a basic lining of magnesite brick. There are two main stages in the operation of Bessemerizing copper mattes. The first is essentially the elimination of the iron sufide; the second, the final sulfur elimination. During the first stage the oxygen of the air blown into the molten matte forms oxides of iron, sulfur, and copper, and the last immediately reacts with the remaining iron sulfide, re-forming copper sulfide with the production of more iron oxide. The iron oxide now reacts with the silica which has been introduced with the charge or during the blow, and produces a great quantity of ferrous silicate slag which must be poured off at the end of this stage. The sulfur oxidizes to sulfur dioxide, which is driven off. The product of the first stage of converting is a "white metal," which is practically pure copper sulfide.

In the second stage the white metal is blown to produce *blister* copper, the sulfur being eliminated by the action of copper oxide, first produced, on the copper sulfide present. The progress of the operation is judged principally by the appearance of the converter flames. Blowing in each stage requires about 60 minutes.

Pyrite Smelting. This term is applied to the smelting of a pyritous ore mainly by the heat of combustion of its own sulfide constituents. It is a process of smelting raw ore in a blast furnace, and the expense of the usual roasting treatment is therefore saved. Pyrite smelting is practiced only by a few American smelters. Ores suitable for pyrite smelting must contain a large amount of iron sulfide. Pyrite smelting requires more flux than ordinary smelting, makes more slag, causes a greater metal loss, and requires a stronger blast pressure.

Alternate Oxidation and Reduction. The method consists in a long series of alternate calcinations and fusions in the reverberatory furnace. The removal of impurities is imperfect, but the sulfur is gradually driven off and the other impurities become segregated in a portion of the product. The process is used to some extent abroad but was abandoned in this country long ago.

With only minor exceptions, all the products from the foregoing processes must be further subjected to a refining treatment before being marketed. Two general methods of refining are available, electrolytic refining, and fire or furnace refining. The electrolytic is now the method most commonly applied. Fire refining in a reverberatory furnace still possesses some commercial value, however; it is based upon the scorifying effect of cuprous oxide upon base metals contained in a batch of molten copper. Fire-refined copper is relatively impure compared with electrolytic copper. In the United States fire-refined copper is poured into ingots for the purpose of making copper and copper-alloy castings.

In addition to the above-mentioned methods, all of which may be characterized as dry methods, there are wet or chemical methods, depending upon getting the copper into aqueous solution by means of suitable solvents and subsequently recovering it from the solution by electrolysis or by means of suitable precipitants.

200. The Properties and Uses of Copper. The properties of copper that possess the greatest practical importance are its electrical conductivity (or conversely, resistivity), its tensile properties, and its resistance to corrosion.

Electrical Resistivity. The maximum resistivity of various classes of copper and copper products permitted under the standard specifications of the American Society for Testing Materials is as follows, the resistivity being expressed in international ohms per meter-gram at 20° C. (68° F.):

Low-resistance lake copper wire bars (annealed)		0.15436
High-resistance lake copper (minimum)		0.15694
Electrolytic copper wire and cakes, slabs, and billets for electrical purposes		0.15436
Electrolytic copper ingots and ingot bars, cakes, slabs, and billets not intended for electrical uses		0.15694
Hard-drawn copper wire	diameters 0.460 to 0.325 in	0.15775
	diameters 0.324 to 0.040 in	0.15940
Medium-hard-drawn copper wire	diameters 0.460 to 0.325 in.	0.15694
	diameters 0.324 to 0.040 in.	0.15857
Soft or annealed copper wire		0.15614

The electrical conductivity is principally dependent upon the purity of the copper, and the specifications for lake and electrolytic copper therefore contain the following stipulations as to the minimum metal content:

Class of Copper	Minimum Metal Content
Low-resistance lake copper.....	99.900 (silver counted as copper)
High-resistance lake copper....	99.900 (silver and arsenic counted as copper)
Electrolytic copper (all shapes).	99.900 (silver counted as copper)

Tensile Properties. The tensile properties of hard-drawn, medium hard-drawn, and soft or annealed copper wire of various sizes specified by the American Society for Testing Materials are indicated in Table XII.

The gradual increase in the tensile strength requirement and the decrease in ductility called for, as the size of wire becomes smaller, is in conformity with the well-known fact that the tensile strength increases rapidly, and ductility decreases, as the amount of cold-working to which the copper is subjected in drawing increases, Fig. 65 (*a*). The effect of partial and complete annealing is also recognized by the slightly lower strength values and slightly higher degree of ductility called for in medium hard-drawn wire, and the much lower strength and very much greater ductility required in the soft wire, Fig. 65 (*b*).

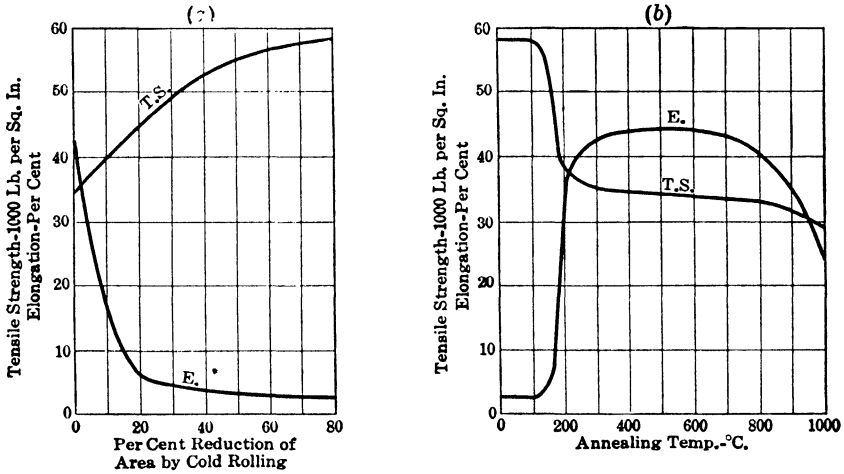

Fig. 65.

(*a*) Effect of Cold-rolling Copper.
(*b*) Effect of Annealing Cold-rolled Copper at Various Temperatures.

The yield point of copper wire does not appear distinctly in tests, and the stress-strain curve exhibits no sudden break, as they do for mild and medium steels. Tests made by members of the committee which framed the above specifications established the average value of the elastic limit

TABLE XII

A.S.T.M. Specifications for Copper Wire

Diameter, in.	Area, cir. mils[1]	Hard-drawn Wire		Medium Hard-drawn Wire			Soft Wire	
		Minimum Tensile Strength, lb. per sq. in.	Minimum Elongation, per cent in 10 in.	Tensile Strength Minimum, lb. per sq. in.	Tensile Strength Maximum, lb. per sq. in.	Minimum Elongation, per cent in 10 in.	Minimum Tensile Strength, lb. per sq. in.	Minimum Elongation, per cent in 10 in.
0.460	211,600	49,000	3.75	42,000	49,000	3.75	36,000	35
0.410	168,100	51,000	3.25	43,000	50,000	3.60	36,000	35
0.365	133,225	52,800	2.80	44,000	51,000	3.25	36,000	35
0.325	105,625	54,500	2.40	45,000	52,000	3.00	36,000	35
0.289	83,520	56,100	2.17	46,000	53,000	2.75	37,000	30
0.258	66,565	57,600	1.98	47,000	54,000	2.50	37,000	30
0.229	52,440	59,000	1.79	48,000	55,000	2.25	37,000	30
			Per Cent in 60 in.			Per Cent in 60 in.		
0.204	41,615	60,100	1.24	48,330	55,330	1.25	37,000	30
0.182	33,125	61,200	1.18	48,600	55,660	1.20	37,000	30
0.165	27,225	62,000	1.14	......	......	......	37,000	30
0.162	26,245	62,100	1.14	49,000	56,000	1.15	37,000	30
0.144	20,735	63,000	1.09	49,330	56,330	1.11	37,000	30
0.134	17,956	63,400	1.07	......	......	......	37,000	30
0.128	16,385	63,700	1.06	49,600	56,660	1.08	37,000	30
0.114	12,995	64,300	1.02	50,000	57,000	1.06	37,000	30
0.104	10,815	64,800	1.00	......	......	......	37,000	30
0.102	10,404	64,900	1.00	50,330	57,330	1.04	38,500	25
0.092	8,464	65,400	0.97	......	......	......	38,500	25
0.091	8,281	65,400	0.97	50,660	57,660	1.02	38,500	25
0.081	6,561	65,700	0.95	51,000	58,000	1.00	38,500	25
0.080	6,400	65,700	0.94	......	......	......	38,500	25
0.072	5,184	65,900	0.92	51,330	58,330	0.98	38,500	25
0.065	4,225	66,200	0.91	......	......	......	38,500	25
0.064	4,096	66,200	0.90	51,660	58,660	0.96	38,500	25
0.057	3,249	66,400	0.89	52,000	59,000	0.94	38,500	25
0.051	2,601	66,600	0.87	52,330	59,330	0.92	38,500	25
0.045	2,025	66,800	0.86	52,660	59,660	0.90	38,500	25
0.040	1,600	67,000	0.85	53,000	60,000	0.88	38,500	25
0.021	....	......	......	......	......	......	38,500	25
0.020	....	......	......	......	......	......	40,000	20
0.003	....	......	......	......	......	......	40,000	20

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[1] One circular mil = 0.0000007854 square inch.

of hard-drawn wires at 55 per cent of the specified ultimate tensile strength for the wires more than 0.324 inch in diameter, and 60 per cent for wires less than 0.325 inch in diameter. For medium hard-drawn wire the average value of the elastic limit was found to be 50 per cent of the specified tensile strength. The modulus of elasticity of drawn copper is usually found to be in the neighborhood of 16,000,000 pounds per square inch.

The tensile properties of copper in forms other than wire are not commonly specified. Hot-rolled plate shows an elastic limit usually not above 7000 or 8000 pounds per square inch, and an ultimate tensile strength of 30,000 to 40,000 pounds per square inch. By finishing cold or by cold hammering its elastic limit may be more than doubled, the tensile strength being increased in a lesser degree.

Corrosion Resistance. Copper has great resistance to corrosion under a wide range of conditions. It is resistant to atmospheric and sea-water corrosion. Owing to its resistance to attack by many industrial chemicals, copper is extensively used for pipes, tubes, stills, condensers, evaporators, autoclaves, and pumps. Copper should not be used, however, in contact with oxidizing acids and most oxidizing agents or where the metal will be subjected to alternate exposure to oxidizing conditions and acid reagents. Copper is not resistant to corrosion by ammonia and carbon dioxide. Other metals which have greater strength and lower cost but poorer resistance to corrosion are often covered or lined with copper.

ZINC

201. Commercial Forms of Zinc. Zinc occurs to some extent in almost every important political division of the world, usually as a sulfide, a carbonate, or a silicate. It is used not only as metallic zinc, in which form it is known to trade as "spelter," but also as zinc dust, which is formed in the distillation of zinc, and as zinc pigments, such as zinc oxide, leaded zinc oxide, and lithopone.

202. Extraction of Zinc from Its Ores. The chemical properties of zinc are so different from those of other common metals that the metallurgical methods by which metallic zinc is derived from ores are unique. Whatever the original state of the zinc in the ore, it must be in the form of an oxide before the metallic zinc is obtainable. In this form it may be reduced by carbon at high temperature, but this temperature is above the volatilizing point of the metal, so that it is always obtained as a vapor which must be condensed. Moreover, zinc vapor must be condensed at a temperature above the point of fusion if the metallic zinc is to be obtained in the more commonly useful commercial form, as spelter. Otherwise, a powder known as "zinc dust," or "zinc fume," is produced. This dust has certain special uses, but oxidizes very readily and cannot be remelted and cast to form spelter. A further complication is introduced by the fact that zinc cannot be reduced in the presence of even minute quantities of carbon dioxide without becoming oxidized, and it is therefore essential that the reduction be accomplished in the presence of an excess of carbon and in a closed retort without access of air.

Another method consists in leaching roasted sulfide and electrolyzing the solution.

203. Properties and Uses of Zinc. Commercial metallic zinc, or spelter, contains varying amounts of impurities up to a maximum permissible amount of about 1.5 per cent for the lowest grade. The principal impurities are lead, iron, and cadmium, according to the content of which spelters are divided into six grades by the American Society for Testing Materials, as given in Table XIII.

TABLE XIII

A.S.T.M. SPECIFICATIONS FOR ZINC

Grade	Maximum Content of Lead, per cent	Maximum Content of Iron, per cent	Maximum Content of Cadmium, per cent	Maximum Content of Lead, Iron, and Cadmium, per cent
1a. Special high-grade	0.010	0.005	0.005	0.010
1. High-grade	0.07	0.03	0.07	0.10
2. Intermediate	0.20	0.03	0.50	0.50
3. Brass special	0.60	0.03	0.50	1.00
4. Selected	0.80	0.04	0.75	1.25
5. Prime western	1.60	0.08	....	....

Grades 1a, 1, 2, 3, and 4 shall be free from aluminum.

Lead in moderate quantities tends to make spelter softer in rolling, but weakens the coating formed in galvanizing. In quantities above about 0.7 per cent, it causes castings to crack badly. Iron hardens spelter and renders it more brittle. An excessive amount of dross is formed in galvanizing. Cadmium hardens spelter and makes it brittle. It is therefore particularly undesirable in galvanizing, because the coating is easily cracked off. Cadmium also tends to cause cracking of castings.

Zinc exhibits a certain amount of creep at ordinary temperatures and consequently is seldom used to withstand stress in a structure or machine. Attempts have been made to utilize solid zinc corrugated sheets for roofing, but these sheets tend to sag when placed on purlins spaced according to standard galvanized-iron practice.*

Since zinc is a plastic metal, its tensile strength as determined by test is dependent upon the rate of application of load. Cast zinc when slowly tested shows a tensile strength of 5000 to 10,000 pounds per square inch and is non-ductile. It becomes malleable when heated to 100° C. to 150° C. (212° F. to 302° F.) and may be rolled into sheets. Zinc which has been rolled and then annealed at 200° C. (392° F.) has a tensile

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* E. A. Anderson: Zinc in the Chemical Industries, *Mechanical Engineering* December, 1936, p. 799.

strength of about 16,000 pounds per square inch and a ductility of about 5 per cent in 8 inches when load is applied at a slow rate parallel to the direction of rolling. The tensile strength perpendicular to the direction of rolling is about 20,000 pounds per square inch, but the ductility is reduced. When the load is rapidly applied, the tensile-strength values are increased to as much as 26,000 and 32,000 pounds per square inch, respectively.

Spelter is used as a galvanizing coating on iron and steel, being applied by dipping or by electrolysis. Zinc is above iron in the electromotive series and will protect iron from corrosion long after the zinc layer is broken because, when iron and zinc are in contact, the zinc becomes the anode in an electrolytic couple which prevents rusting of the steel over an area adjacent to the coating. Protection may be obtained over a distance as great as ¼ inch in seashore atmospheres where the conductivity of the moisture film connecting the iron and zinc surfaces is improved because of dissolved gases and salts in the moisture film.* This fact is utilized to prevent the corrosion of marine hardware, marine boilers and condensers, and also parts of the hulls of ships.

A considerable quantity of spelter is rolled into sheet zinc. A further quantity is used in making castings, and a considerable amount in combination with copper and other metals in making brass and other alloys. Zinc is common as the negative pole in batteries. Since zinc melts at 419° C. (786° F.), it cannot be used in high-temperature work.

The various zinc pigments made from zinc or zinc ore are much used. Zinc oxide is the most important of these, but leaded zinc oxide, zinc-lead oxide, and lithopone (a mixture of chemically precipitated zinc sulfide and barium sulfate) are used to a certain extent as white pigments for mineral paints.

A large amount of zinc in the form of zinc chloride is also utilized as a wood preservative.

LEAD

204. Commercial Forms of Lead. Lead occurs in almost every part of the world, usually as a sulfide, but sometimes as oxidized decomposition products of the original sulfide. It usually occurs associated with a small amount of silver, and often its ores contain a considerable amount of antimony.

Owing to the common occurrence of silver and antimony in lead ores, and the fact that these metals are not removed by the ordinary process of smelting, the output of lead smelters is classed under three heads as follows:

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* E. A. Anderson, *ibid.*

Soft lead is obtained by smelting ores which are normally so low in silver that desilverization is not necessary or practical.

Desilverized lead is that obtained by special desilverizing treatment of the ordinary argentiferous lead ores.

Antimonial lead is that which carries an average of about 17 per cent of antimony and about 2 per cent of other metals such as arsenic and copper. It is, of course, an alloy and is sometimes called "type metal," since it is often used in type-founding. It is made from the ore, not from pure metals.

In addition to the forms of metallic lead above listed, lead is used commercially in the form of pigments, and as litharge. The principal forms of lead pigments are leaded zinc oxide, which contains from 4 to 20 per cent of lead sulfate, the remainder being zinc oxide with a small portion of zinc sulfate; zinc-lead oxide, containing 46 to 50 per cent of lead sulfate, 46 to 52 per cent zinc oxide, and a small quantity of zinc sulfate; sublimed white lead, which consists of 50 to 53 per cent lead sulfate, 38 to 41 per cent lead oxide, and small proportions of lead sulfide, lead sulfite, and zinc oxide. All these lead pigments are used as white pigments in the manufacture of mineral paints.

Litharge is lead oxide (PbO), containing 92.83 per cent of lead. It is produced direct from ore, or may be prepared by heating metallic lead in a current of air. It is used in making flint glass, in glazing pottery, and as an oxidizing agent in many processes, besides having many other commercial applications.

205. Extraction of Lead from Its Ores. The metallurgical processes involved in the extraction of lead from its ores comprise the following operations: roasting or sintering of the ore, smelting in the blast furnace, and a number of secondary operations, including treatment of the matte which forms a portion of the products of the blast furnace, the recovery of dust from roasting and smelting furnaces and from matte converters, and the desilverizing of the lead if the silver content is sufficient to justify it.

The methods of roasting lead sulfide ore consist essentially in forcing air through finely divided metallic sulfide with the object of partly removing the sulfur, oxidizing the metal, and agglomerating the material in a form suitable for use in the blast furnace.

Lead ores are smelted in rectangular blast furnaces which closely resemble those for copper smelting.

Lead derived by the general methods described above usually contains varying amounts of arsenic, antimony, tin, zinc, nickel, cobalt, iron, sulfur, copper, and bismuth, in addition to silver, and their removal before marketing the lead is necessary if they exceed limited proportions.

206. Properties and Uses of Lead.* The only physical properties of lead commonly taken into account are its plasticity, its malleability, and its resistance to corrosion. Lead gradually elongates under sustained stress at ordinary temperature. The creep limit of lead is approximately a fiber stress of 200 pounds per square inch at room temperature with some variation depending upon composition or heat treatment. Pure commercial lead (99.9 per cent lead) shows a tensile strength of 1900 pounds per square inch and an elongation of 55 per cent when tested at the rate of 0.25 inch per inch per minute, but owing to the plasticity and creep characteristic of lead these values would vary greatly with change in rate of application of load; indeed, it is questionable whether the results of instantaneous tensile-strength tests of lead have much significance.

Pure commercial lead has been reported to have an endurance limit of about 400 pounds per square inch.

Because of its plasticity and malleability, lead is easily rolled into sheets or extruded in the form of tubes, pipes, rods, ribbons, and wires.

The high resistance of lead to corrosion is due to the formation of a protective oxide film over the surface. Such a film may vary from an oxide tarnish to a heavy coat and has the characteristic of "self-healing." In general, lead is resistant to corrosion by the atmosphere, natural waters, and most mineral acids in which an insoluble product is formed. Steel pipes, tanks, etc., are coated with lead, and many water pipes and conduits for electrical conductors are made of lead. Because of danger to health, lead pipes should not be used for very soft drinking waters and those containing magnesium chloride or a high content of free carbon dioxide, but tin-lined lead pipes are safe for carrying soft drinking water. Lead is used in equipment for handling many chemicals and reagents including sulfuric acid.

Lead is often used because of its great density; it weighs approximately 707 pounds per cubic foot.

Antimony, arsenic, copper, and zinc harden lead, when present to any considerable extent, but, with the exception of antimony, they are seldom present in refined lead to an extent which renders their effect appreciable. Antimonial lead, or "hard lead," is used as type metal, bearing metal, and for shot and bullets. Lead for rolling into sheet metal and for pipes must be as free as possible from antimony and arsenic as well as metallic sulfides or other hardening elements.

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* G. O. Hiers: Corrosion-resistant Lead Equipment, *Mechanical Engineering* December, 1936, p. 793.

TIN

207. Commercial Forms of Tin. Tin is used quite extensively in the form of sheet tin and as tinfoil, but has almost no other commercial application except as a constituent of many valuable alloys. A limited but important use is in the making of boiler fuse plugs, for which purpose it must be of the highest purity. Tin is one of the few important metals that are not abundant in the United States. The principal sources of tin are the Federated Malay States in the East Indies (referred to as the Straits or Straits Settlements), England, Australia, and Bolivia. In the United States, only relatively small amounts of tin are mined, the principal source being Alaska.

208. Extraction of Tin from Its Ore. The extraction of tin from its ore involves the mechanical, or combined mechanical, thermal, and chemical, concentration of the ore, reduction by smelting with charcoal or coke in shaft furnaces or reverberatory furnaces, and refining of the crude tin derived by smelting.

The most common refining treatment is simply a liquation process, the pure tin being melted out on a hearth and allowed to escape while the less fusible alloys of the impurities remain behind as liquation dross.

209. Properties and Uses of Tin. The properties of tin of commercial importance are its great malleability at ordinary temperatures, and its high resistance to corrosion when pure. A large amount of the world's production is used as a coating on sheet iron or steel. A smaller proportion is cold-rolled into sheet tin and used in the manufacture of roofing material, tinfoil, etc. Tin is effective as a coating as long as the surface remains unbroken, but will not protect the iron after the surface is broken as zinc will, since tin is below iron in the electromotive series. Tin tends to creep under sustained stress at ordinary temperature.

When heated above atmospheric temperatures tin becomes brittle, until at 200° C. (392° F.) it can be powdered by hammering. Iron in considerable amounts makes tin hard and brittle and less rust-resistive. Arsenic, antimony, and bismuth, in amounts exceeding about 0.05 per cent, lower its strength considerably; copper and lead (1 to 2 per cent) increase its hardness and strength, but render it less malleable.

ALUMINUM

210. Commercial Forms of Aluminum. Practicable processes for the production of metallic aluminum have been developed since 1886. Prior to that time the metal was merely a chemical curiosity, but since the discovery of electrolytic extraction methods it has assumed a position of great importance. It is recommended particularly by its lightness (sp. gr. = 2.60–2.74) combined with considerable strength, great ductility, high heat and electric conductivity, malleability, non-corrosiveness, and immunity from attack of certain acids.

Aside from its very common use as rolled, pressed, drawn, or cast metal, metallic aluminum is utilized in the form of aluminum foil, like tinfoil, and powdered aluminum as a paint pigment, in explosives, in lithographing and printing, and in the *Thermit* process of welding.

211. Extraction of Aluminum. Aluminum is one of the most abundant elements in the world; yet there are few minerals from which it has been successfully extracted. The most important are bauxite and cryolite; rocks containing aluminum sulfate, kaolin, and clay are of much less importance. Whatever the original source of the material, it is converted into alumina (Al_2O_3) before the metal is extracted.

Bauxite is a mixture of alumic and ferric hydrates containing widely varying amounts of alumina, ferric oxide, silica, calcium, and magnesium carbonates, water, etc. Most bauxites carry from 40 to 55 per cent alumina.

Cryolite is a double fluoride of sodium and aluminum, represented by the formula $Al_2F_6 + 6NaF$, and containing, when pure, 13.07 per cent aluminum.

The only methods of extraction of aluminum of commercial importance consist in the electrolysis of comparatively pure alumina dissolved in a bath of molten cryolite. Alumina for the purposes of electrolysis is usually made from bauxite, but may be prepared by treating siliceous bauxite, kaolin, or clay with sulfuric acid, and subsequently driving off the sulfuric acid from the aluminum sulfate produced, by ignition. Bauxite is treated with a soda solution, and the alumina is extracted as sodium aluminate. The alumina may be precipitated from the solution as hydroxide by carbon dioxide, and subsequently washed, filtered, and dehydrated by heating, or it may be precipitated as hydroxide by stirring the solution with pure aluminum hydroxide.

The metal derived as the product of the above operations is commercial aluminum, and is usually about 98 to 99.5 per cent pure. Special grades are obtainable, containing as much as 99.9 per cent aluminum, and some second-grade metal is sold which contains not over 95 or 96 per cent aluminum. The principal impurities are silicon and iron.

212. Properties and Uses of Aluminum. The general properties of commercial aluminum are indicated by Table XIV. The minimum values apply to metal in an annealed condition, and the maximum values to metal that has been cold-worked to an extreme degree by forging, cold-rolling, or drawing, without subsequent annealing.

The very marked effect of cold-working in increasing the strength and improving the elastic properties of the metal is exhibited by the above maximum values. The ductility is very considerable, and the

TABLE XIV

TENSILE PROPERTIES OF ALUMINUM [1]

Form	Tensile Strength, lb. per sq. in.	Yield Point, lb. per sq. in.	Elongation in 2 inches, per cent	Reduction of Area, per cent
Sand-cast	11,000–13,000	8,500	15–25	
Chill-cast	12,000–14,000	9,000	15–25	
Sheet:				
Annealed	12,000–15,000	8,000–9,000	12–35	20–30
Half-hard	18,000–22,000	9,000–12,000	5–10	20–30
Hard	22,000–35,000	12,000–25,000	1–7	20–30
12-gauge	25,000		7	
16-gauge	28,000		5	
20-gauge	30,000		3	
Bars (hard)	28,000–35,000	14,000–23,000		30–40
Wire (hard)	25,000–55,000	16,000–33,000		40–50
40-mil	31,000			
80-mil	28,000			
120-mil	25,000			
200-mil	22,000			

[1] Circular 76 of the Bureau of Standards.

metal works well, at temperatures below about 200° C. (392° F.), in rolling or forging. Cold-working hardens aluminum excessively, and in wire-drawing the metal must be frequently annealed to restore ductility.

The low electrical resistance of aluminum is one of its most valuable properties, since a relatively high conductivity, combined with its lightness and strength, makes it especially well adapted for long-span transmission lines. Pure aluminum is being used extensively in electrical work both as bus bars and rods in power stations and in large quantities for transmission lines with high voltages. Aluminum wires of about the same electrical conductivity as copper are enough larger so that corona losses are much less. With regard to equivalent conductivities, it has been calculated that 1 pound of aluminum is equivalent to about 1.6 pounds of copper.

Aside from the electrical uses of metallic aluminum, large quantities are consumed in the manufacture of many articles of everyday domestic use and in many industries where tanks, cooking vats, etc., which must be heat-conductive, non-corrodible, and non-poisonous, are used. For these purposes the metal is either cast or rolled, and many articles are finished in a press. A further quantity of aluminum is finished in the form of seamless tubing which has many important applications.

Aluminum is resistant to atmospheric corrosion and is little affected by most neutral salts, most organic acids (except formic, oxalic, and acetic acids), many organic solvents, and generally dry gases. Aluminum is generally attacked by acid and alkaline salt solutions, sodium and potassium hydroxide solutions, and mineral acids such as halogen acids and intermediate concentrations of nitric and sulfuric acids.

Aluminum has the high thermal coefficient of expansion of 0.000025 per degree C. and a high thermal conductivity (0.475 gram-cal. per sec. per cm.-cube per degree C.). It therefore expands a great deal upon being heated but has the ability to carry heat away rapidly. Its melting point is 659° C. (1218° F.).

Aluminum is suitable for casting purposes where lightness and softness are required rather than hardness and strength. Most of the aluminum used for these purposes, however, is alloyed with other metals which harden it and materially increase its strength. Much of the rolled and drawn aluminum is also slightly alloyed, with an improvement in strength and hardness.

MAGNESIUM

213. Commercial Forms of Magnesium. Magnesium is a light metal (sp. gr. = 1.7) which has considerable strength, fair ductility, and high heat conductivity. It is used principally as a constituent of light-weight alloys.

214. Extraction of Magnesium from Its Ore. Compounds of magnesium occur in extensive, widely distributed deposits suitable for the manufacture of magnesium metal. Magnesium is the sixth most abundant element in the earth's crust. At the present time magnesium is produced by the electrolysis of magnesium chloride, which is obtained as a by-product from the process of purifying sodium chloride derived from brine wells. A molten bath of magnesium chloride mixed with sodium and potassium chloride is electrolyzed at a temperature of about 700° C. The presence of sodium and potassium chloride is necessary to prevent decomposition of the magnesium chloride during heating. The process is carried out in an air-tight container. Chlorine gas is liberated at the anode and magnesium at the cathode, where it rises to the surface because of its lightness and is poured off. This magnesium metal contains some non-metallic impurities which may be largely eliminated by reheating in a vacuum or in contact with a flux to prevent oxidation. Owing to its relatively low boiling point (1120° C. [2048° F.]), impurities can be removed by distillation.

Formerly magnesium was obtained by an oxide process similar to the electrolytic process for the production of aluminum.

215. Properties and Uses of Magnesium. Magnesium has a tensile strength when cast of about 14,000 pounds per square inch, its compressive strength is about 24,000 pounds per square inch, its elongation in

2 inches is about 5 per cent, and its Brinell hardness is about 30. When rolled it has a tensile strength of about 25,000 pounds per square inch, an elongation in 2 inches of 4 per cent, and a Brinell hardness of about 40. Magnesium has the high thermal coefficient of expansion of 0.000029 per degree C. and a high thermal conductivity (0.376 gram-cal. per sec. per cm.-cube per degree C.). Thus magnesium expands a great deal upon being heated, but has the advantage of carrying heat away rapidly. Its melting point is 651° C. (1204° F.). Magnesium in finely divided particles ignites easily. A coating of magnesium hydroxide is formed in humid air which protects it from further oxidation. Magnesium is not used alone structurally, but alloys containing magnesium are employed for structural parts principally because of their light weight.

NICKEL

216. Commercial Forms of Nickel. Metallic nickel is becoming increasingly valuable in the production of materials which must possess strength and resistance to corrosion. It is used in the manufacture of nickel and other alloy steels and nickel cast iron; a further quantity, in alloys of non-ferrous metals; and a small quantity, as anode plates for electrolytic nickel plating of various metals. In the form of the double sulfate with ammonium ($Ni(NH_4)_2(SO_4)_2$), it is also used as the electrolyte in nickel plating.

217. Extraction of Nickel from Its Ores. The methods of extraction of nickel from sulfur compounds, after removal of gangue, involve principally the separation of nickel from sulfur and from iron, and in most ores from copper also. The first operation consists in roasting the pyrite ore, the object of which is to remove sulfur until only enough remains to combine with nickel, copper, and a portion of the iron during the smelting operation which follows.

The second step in the process is the smelting of the roasted ore in a blast furnace. All the iron that has previously been oxidized passes into the slag; the residue of undecomposed iron sulfide forms a matte containing all the nickel and copper sulfides.

Complete separation of the iron cannot be effected in the smelting operation because of the loss of nickel in the slag that would result, and the next step in the operation is therefore the removal of the iron sulfide by an oxidizing fusion. This operation is accomplished in a converter, and the removal of iron is complete.

Metallic nickel and copper are derived from the refined matte by repeated smelting, by electrolysis, and by volatilizing as an organic nickel compound.

218. The Properties and Uses of Nickel. The most important property of nickel, aside from the advantages which it may confer upon ferrous or non-ferrous metals with which it is alloyed, is its resistance to corrosion. Nickel is highly resistant to atmospheric, fresh-water, and salt-water corrosion, and it resists attack by neutral and alkaline salt solutions and by alkalies. On this account, and because of its silvery appearance, one of the commonest commercial applications of metallic nickel is in plating iron, steel, or other metals. (Chromium coatings, however, are more durable than nickel.)

The mechanical properties of nickel are excellent, sometimes equaling those of medium-carbon steel, but it is too expensive for general use. It is quite ductile and fairly malleable, but is rendered brittle and incapable of being rolled by not more than 0.1 per cent of arsenic or sulfur. Most of the other impurities common to commercial nickel are not injurious to its properties, and some are beneficial in limited amounts.

Nickel is available in various forms, such as hot-rolled rods, hard- or soft-rolled sheets, hard- and soft-drawn wires, castings, and shot for alloying purposes. The hardness and tensile properties of "A" or 99 per cent nickel are shown in Table XV.

TABLE XV

TENSILE PROPERTIES AND HARDNESS OF 99 PER CENT NICKEL[1]

Form of Nickel	Yield Point, lb. per sq. in.	Tensile Strength, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Brinell Hardness (3000 kg.)
Hot-rolled rods.....	20- 30,000	70- 80,000	40-50	50-70	100-120
Annealed sheet.....	15- 25,000	60- 75,000	35-45	.....	80-100
Cold-rolled sheet...	85-105,000	90-110,000	1-2	.....	130-160
Annealed wire......	15- 25,000	60- 75,000	20-30	.....	....
Hard-drawn wire...	110-130,000	120-140,000	1-2	.....	....
Castings...........	20- 30,000	50- 60,000	20-30	.....	80-100

[1] Circular 100 of U. S. Bureau of Standards.

The modulus of elasticity of 99 per cent pure nickel is slightly higher than that of steel (30–33,000,000 pounds per square inch), and Poisson's ratio for nickel has been stated to be 0.33. Nickel retains its tensile strength, yield point, and ductility at elevated temperatures.

THE PRINCIPAL NON-FERROUS ALLOYS

219. Classification. A very large number of non-ferrous alloys have been listed, but only the common ones will be considered here. These are arranged in the following groups:

(*a*) Alloys in which copper is the chief constituent.

(*b*) Alloys in which aluminum is the principal metal.

(*c*) Other non-ferrous alloys as, for example, magnesium alloys and nickel alloys.

(*d*) Die-casting alloys.

(*e*) Bearing metals and fusible alloys.

In the group of copper-base alloys the most important types are essentially copper and tin (the *bronzes*), copper and zinc (the *brasses*), and copper associated with nickel or with aluminum.

THE COPPER ALLOYS

220. Ordinary Bronzes. The influence of tin upon the properties of copper is that of a pronounced hardener and strengthener, so long as a limiting percentage of 20 or 25 per cent is not exceeded. The range of composition of ordinary commercial bronzes is not broad, all the important ones containing 80 per cent or more of copper.

A solid solution of copper and tin known as the "alpha" phase exists for tin contents up to approximately 12 per cent. For tin contents ranging from 12 to 28 per cent approximately, a "delta" phase occurs, producing a mixture of alpha and delta phases.

Many alloys known as bronzes are not true bronzes and should be classed as brasses or in special groups. Bronze, as a name, conveys the idea of a higher-class alloy than brass, and for this reason the word has been used promiscuously in naming alloys that are chemically not entitled to such classification. For example, *Tobin bronze,* which contains 60 per cent Cu, 38 per cent Zn, and 2 per cent Sn, should be known, not as a bronze, but as a brass.

Fig. 66 summarizes the average mechanical properties of a series of bronzes tested by the U. S. Test Board under the supervision of Professor Robert H. Thurston.

The bronzes exhibiting the greatest tensile strength and bending strength, and the highest yield point, are those containing more than 80 per cent of copper. The compressive strength increases with decrease in copper content until an alloy containing about 75 per cent of copper and 25 per cent of tin is passed. Beyond these limits the strength decreases rapidly with further additions of tin. The stiffness increases until a 50 per cent tin alloy is reached, but the ductility reaches its maximum with only about 4 per cent of tin, and is entirely lacking with more than 25 per cent. When the high-tin alloys are reached the great ductility of the tin becomes a characteristic. All the alloys containing between 25 and 75 per cent of tin are extremely brittle and weak, and those containing more than 75 per cent of tin are weak and soft.

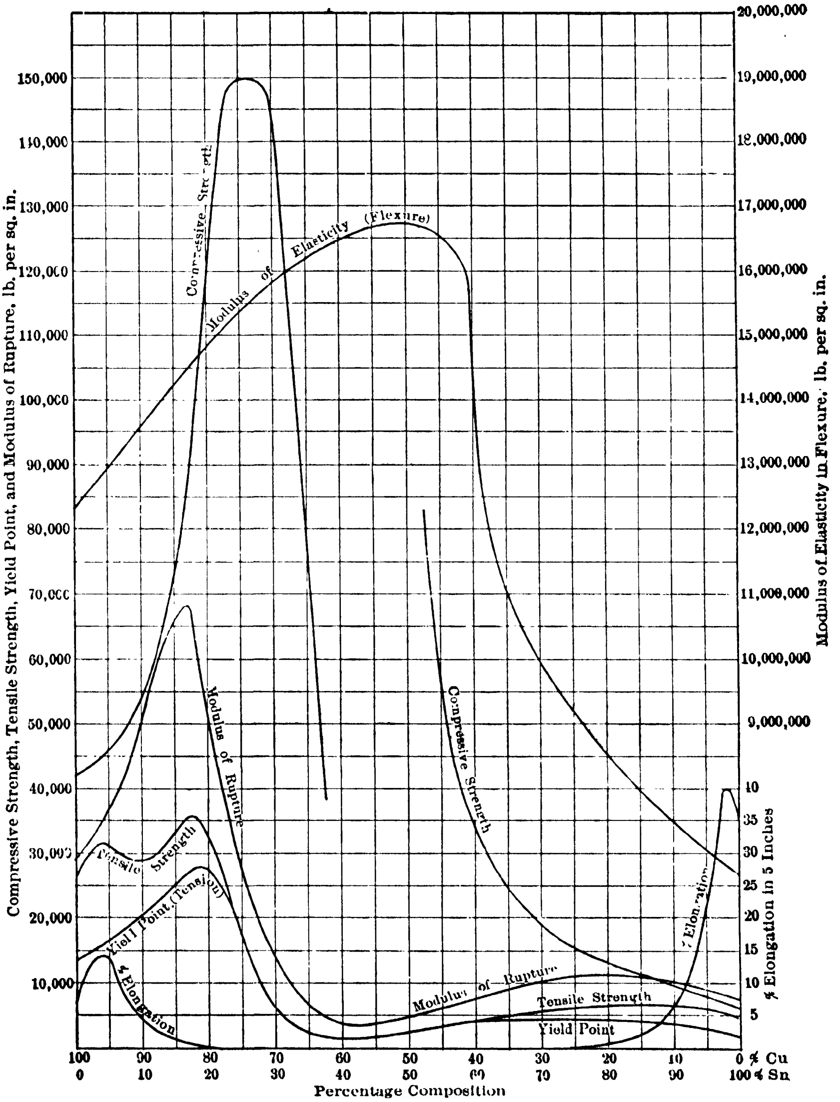

FIG. 66.—Properties of the Copper-tin Alloys. (U.S. Test Board.)

The strength and ductility of bronzes are considerable affected by heat treatment. M. Guillet found that, with bronzes containing over 92 per cent of copper, quenching between 400° C. (752° F.) and 600° C. (1112° F.) slightly increases the strength and ductility. With less than 92 per cent of copper, both strength and ductility increase decidedly as soon as the quenching temperature exceeds 500° C. (932° F.). The maximum strength of all alloys was found to be reached by quenching at about 600° C. (1112° F.), the beneficial effect becoming more marked as the copper content is reduced.

Among the common bronzes are the following (it will be noted that a number of these alloys classed as ordinary bronzes contain small amounts of zinc, lead, etc.):

Machinery bronzes are used principally as hard bearing metal, as metal for cut gears, for valves, bushings, stuffing boxes, piston rings, steam whistles, plumbing fixtures, etc. The average machinery bronze contains from 81 to 87 per cent of copper and 19 to 13 per cent of tin. Most gear bronzes contain phosphorus or manganese or both, and will therefore be considered as phosphor or manganese bronzes.

Gun metal usually contains from 88 to 92 per cent of copper and 12 to 8 per cent of tin. It is one of the strongest of all the bronzes. At one time guns were commonly cast of it, and it is now used as a material for strong castings. It is not infrequently alloyed with small percentages of zinc or lead.

Phosphor Bronze. The addition of very small percentages of phosphorus to any bronze has a remarkable effect upon its properties. The tensile strength is considerably increased, and the apparent elastic limit and endurance under repetition of stress are greatly increased. Phosphorus added in amounts up to 0.5 per cent acts principally as a deoxidizer, and the marked improvement in the properties of the bronze is principally due to the elimination of copper oxide. For percentages from 0.5 to 1.2, the phosphorus combines with copper to form the compound copper phosphide, which greatly hardens the bronze.

Phosphor bronzes intended for use as engine parts, valve metal, etc., ordinarily show only traces of phosphorus and contain about 7 per cent of tin. Phosphor bronze for gears is harder, owing to the presence of 8 to 12 per cent of tin, and phosphorus varying from mere traces up to a maximum of about 0.2 per cent. Bearing bronzes most commonly contain 8 to 10 per cent of tin and from 0.2 to about 0.9 per cent of phosphorus. Certain bearing bronzes, particularly those for railway service, contain from 10 to 30 per cent of lead. These bronzes excel any other class of bearing metals in resistance to wear under severe conditions, and in addition possess a very low coefficient of friction.

Phosphor bronzes of proper composition may be rolled or drawn into wire, and when so fabricated exhibit about the same tensile properties as medium structural steel. Working cold has the same effect as upon steel, the strength, and especially the elastic limit, being raised to a marked extent. All the phosphor bronzes are remarkably resistant to corrosion and are much utilized on subaqueous construction.

Copper-tin-zinc Bronzes. The copper-tin-zinc alloys are among the most valuable and commonly used of all the bronzes. The range of composition of the commercial bronzes of this class is from 50 to 95 per cent of copper, 1 to 15 per cent of tin, and 5 to 50 per cent of zinc. A very common bronze of this type, containing 88 per cent of copper, 10 per cent of tin, and 2 per cent of zinc, will show a tensile strength of 30,000 to 40,000 pounds per square inch and an elongation of 15 to 30 per cent in 2 inches.

The character and uses of the most important copper-tin-zinc bronzes have been indicated under the head of machinery bronzes. Frequently, bearing bronzes contain from 2 to 4 per cent of zinc. Locomotive bronzes and piston rings may contain as much as 8 or 9 per cent of zinc.

Copper-tin-lead Bronzes. Lead is often added to bronzes used for bearings, for the purpose of increasing the plasticity just enough to allow the metal to adapt itself to the running surface so that the bearing is uniform over the whole surface. (See Fig. 20.) The addition of 10 to 40 per cent of lead to a bronze containing 5 to 10 per cent of tin cuts down the wear on the bearing very materially without increasing the friction to any great extent. The degree of softness desirable in a bearing bronze is dependent upon the conditions of service, and the lead content and tin content are varied accordingly. In general, the lower the content of tin, the higher the content of lead desirable. Several alloys of this class commonly used for railway service and other purposes are known as "plastic bronzes." They contain 50 to 80 per cent of copper, 20 to 50 per cent of lead, and 0 to 5 per cent of tin. Small percentages of other elements, nickel for example, are usually added to prevent segregation of the lead. The composition and properties of some leaded-bronze bearing metals are listed in Table XVI.

Manganese Bronze. The so-called "manganese bronze," which serves a great variety of purposes, is really a special brass, since it contains large amounts of zinc and little or no tin. This class of alloys will therefore be considered under the head of special brasses.

Silicon Bronze. Silicon added to ordinary bronzes has about the same effect as similar additions of phosphorus. Its principal action, when it is added in small quantities, is that of a deoxidizer, and it has about the same effect upon the properties as phosphorus, the strength and especially the elastic limit being raised, although only a trace of silicon may appear in the finished bronze.

TABLE XVI

Composition and Properties of Leaded-bronze Bearing Metals

Alloy Grade No.	Desired Composition			Ultimate Tensile Strength, lb. per sq. in.	Elongation in 2 in., per cent	Brinell Hardness, (500 kg. for 30 sec.)	Shrinkage, in. per ft.	Weight, lb. per cu. in.	Compression Deformation Limit,[1] lb. per sq. in.
	Copper %	Tin %	Lead %						
1	85	10	5	28,000	12.5	60	0.25	0.31	18,000
2	80	10	10	25,000	8	55	0.25	0.31	15,000
3	80	10	10	22,000	8	50	0.25	0.32	12,500
4	77	8	15	20,000	10	48	0.25	0.33	12,000
5	73	7	20	18,000	7	45	0.25	0.33	11,000
6	70	5	25	15,000	5	40	0.25	0.33	10,000

[1] The compression deformation limit is usually taken as the stress producing a deformation in the specimen of 0.001 inch per inch.

In one important respect silicon differs in its effect from phosphorus. Phosphorus, even in very small amounts, is very detrimental to electrical conductivity, but silicon is not. In consequence, silicon bronze is a much better conductor than phosphor bronze, and is used considerably for telephone wires, etc.

Aside from its electrical conductivity, silicon bronze possesses most of the valuable properties of phosphor bronze, and is used for similar purposes where a strong, hard, and non-corrodible alloy is desired in the form of castings, rolled sections or sheets, or drawn wire.

Aluminum Bronze. The alloy commonly known as aluminum bronze contains no tin, but is simply an alloy of copper and aluminum, and so is not really a bronze at all. Its character and properties will be considered under the head of binary alloys of copper other than bronzes and brasses.

Vanadium Bronze. Vanadium has occasionally been added to bronzes in very small amounts with remarkably beneficial effects upon properties.

Statuary Bronze. This is a leaded copper-tin-zinc bronze which develops a film by oxidation known as "patina," giving a sheen or glistening appearance to the surface.

Bell Metal. This bronze contains about 18 per cent tin and has resonance.

Speculum Metal. A bronze containing 33 per cent tin which is silvery in color and has a high reflective surface when polished. It is used in telescopes.

221. Ordinary Brasses. The influence of zinc upon the properties of copper is in the direction of increasing both strength and ductility, so long as certain limiting percentages are not exceeded, but these limiting percentages are much higher than for tin, zinc being a less potent element than tin in similar amounts.

The constitution of brasses having a composition range of zinc up to 35 per cent consists of a single-phase solid solution of copper and zinc known as the "alpha" phase. The space lattice is face-centered cubic in the alpha phase. At a composition of approximately 35 per cent zinc, the space lattice becomes body-centered cubic. Above a zinc content of 35 per cent, a second phase termed the "beta" phase occurs, producing a mixture of two phases. The effect of the beta phase is to strengthen and harden the alloy. As the zinc content increases, the beta phase becomes dominant and the brass becomes brittle and worthless structurally. For the higher percentages of zinc, the copper goes into the space lattice of zinc, the space lattice of the alloy being hexagonal.

Fig. 67 summarizes the mechanical properties of the copper-zinc alloys. The curves are based upon the report of the Committee on Alloys of the United States Board, the fourth report of Professor W. C. Roberts-Austen to the Alloys Research Committee of the Institution of Mechanical Engineers, and an independent study of the tensile strength of the copper-zinc alloys by Dr. J. M. Lohr.

By referring to Fig. 67, it may be seen that the constitution of brass has a direct relationship to mechanical properties. The addition of zinc to copper gradually increases the tensile strength until about 35 per cent is present. Maximum ductility is shown by brass containing from about 25 to 35 per cent of zinc. Additions of zinc up to about 45 per cent rapidly increase the tensile strength but reduce the ductility owing to the presence of the beta constituent. A rapid falling off in tensile strength occurs with additions of zinc beyond 45 per cent, and the brasses containing more than about 50 per cent of zinc are brittle and of no structural value.

A comparison of the curves of Fig. 67 with those of Fig. 66 shows that the best of the brasses excel the best of the bronzes in tensile strength and ductility, but the bronzes seem to excel in compressive strength.

The following are some of the common brasses:

Hard brazing metal contains 80 to 90 per cent of copper and 20 to 10 per cent of zinc.

Red brass usually contains about 80 per cent of copper and 20 per cent of zinc. The name is used loosely, however, to cover any of the high-copper brasses which possess a reddish color, especially after pickling in acid. This class of brass is much used for ornamental work and soft castings.

Standard brass (alpha brass) contains about 66 to 70 per cent of copper and 34 to 30 per cent of zinc. It is one of the most generally useful of all the brasses. It is very ductile, works well hot or cold, and

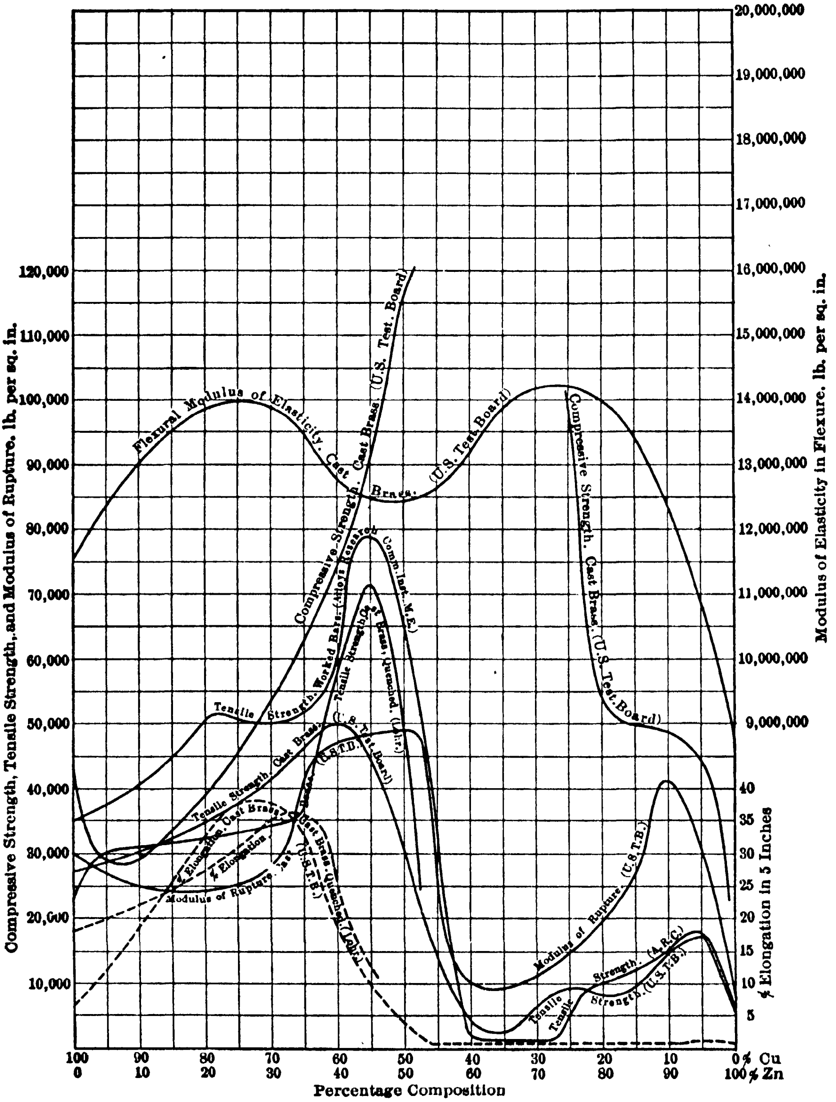

FIG. 67.—Properties of the Copper-zinc Alloys.

can readily be rolled into sheets and drawn into tubes or wire. It is less easily corroded than any of the brasses of lower copper content, and is especially adapted for use in locomotive and steamship boiler and condenser tubes. Practically all ordinary sheet brass and drawn brass is of this composition, and the best of the brass castings contain about 67 per cent of copper.

Brass that is badly overstrained becomes greatly distorted (see Fig. 14), showing such elongation of the crystals as to give the impression of a distinctly fibrous structure under the microscope. When such strained material is annealed a recrystallization of the alloy takes place with the formation of the remarkable condition known as "twinning." This is illustrated by the photomicrographs in Fig. 15 (*A*), corresponding to a low annealing temperature, and (*B*), annealing at a much higher temperature. The marked difference in grain size should be noted. The smaller grains are associated with high tensile strength, hardness and moderate ductility; the large grains indicate low tensile strength and soft metal.

Muntz metal is a brass containing 60 per cent of copper and 40 per cent of zinc. It can only be rolled hot, and was formerly much used as a sheathing for wooden vessels. Sea water attacks it and forms zinc salts, which prevent the fouling of the bottoms of ships by living organisms such as barnacles.

Brass, either of the standard or of the Muntz metal type, and certain other copper alloys are subject at times to a type of failure called *season cracking*. It is apparently due to a combination of unevenly strained metal and a specific corroding agent, commonly either ammonia or one of the salts of mercury. Serious failures caused by this phenomenon have occurred. Recent investigation has shown, however, that the difficulty may be overcome by a low-temperature anneal (300° C. [570° F.]) without materially decreasing the hardness which may have been intentionally produced by cold-working. This operation is known as "semi- or relief-annealing."

Closely associated with standard brass and Muntz metal are the alloys known as *admiralty metal*, or *admiralty brass*, and *naval brass*. The first is made by the addition of about 1 per cent of tin to 70-30 brass, and the second by the addition of the same amount of tin to Muntz metal. The addition of tin, even in the small amounts mentioned, markedly increases the resistance to corrosion. These four alloys: (1) admiralty metal, (2) standard or alpha brass, (3) naval brass, and (4) Muntz metal, have a widely extended use as condenser-tube metal, their value for this purpose being indicated in the order shown above. Admiralty metal is generally accepted as the best condenser-tube material now available; Muntz metal is largely used in fresh, non-corroding waters.

The tensile requirements of the American Society for Testing Materials for naval brass rods for structural purposes are shown in Table XVII.

TABLE XVII

A.S.T.M. TENSILE REQUIREMENTS FOR NAVAL BRASS RODS

Diameter or Distance between Parallel Faces	Yield Point, lb. per sq. in.	Tensile Strength, lb. per sq. in.	Elongation in 2 in., per cent
Up to 1 in., incl.	31,000	62,000	25.0
Over 1 to 2½ in., incl.	30,000	60,000	30.0
Over 2½ to 3½ in., incl.	25,000	56,000	35.0
Over 3½ in.	22,000	54,000	40.0

Yellow brass contains from 48 to 56 per cent of copper and 52 to 44 per cent of zinc. A mixture of approximately equal proportions of the two constituents is common for brass castings that do not require great strength or toughness. At a red heat, yellow brass becomes so brittle that it may easily be pulverized, and in this form it is used for brazing purposes.

White brass solder contains 34 to 44 per cent of copper and 66 to 56 per cent of zinc. It is extremely weak and brittle and is used only in a powdered condition for brazing purposes.

White brass contains less than 10 per cent of copper and more than 90 per cent of zinc. The metal possesses most of the characteristics of zinc, but is somewhat hardened and strengthened by the small amount of copper, the coarse crystalline structure of cast zinc being largely destroyed. The material is principally used in making ornaments which are plated with bronze and sold under the name French bronze.

222. Special Brasses. *Copper-zinc-lead Brasses.* The addition of small percentages of lead softens brass and renders it more easily cut by machine tools, its free-cutting properties being improved so that automatic machines may be employed. The presence of the lead lowers the strength and decreases the ductility considerably. More than 5 per cent of lead cannot be profitably used because of the danger of segregation, and the usual addition is not in excess of 3 per cent.

Copper-zinc-aluminum Brasses. Aluminum is added to brass in amounts up to about 5 per cent with beneficial effects upon the tensile properties. The tensile strength and elastic limit are considerably raised, and the hardness increased and ductility decreased. The effect of aluminum upon the tensile strength and ductility of rolled and cast brass is shown by Fig. 68, which is based upon tests reported by M. Guillet.

The addition of aluminum is also beneficial in that it facilitates the making of good brass castings. Aluminum brass is principally used in making castings for machinery, marine work, etc., for forgings, and for rolled bars, plates, and shapes designed for any purpose requiring a strong brass, or a strong and non-corrodible metal.

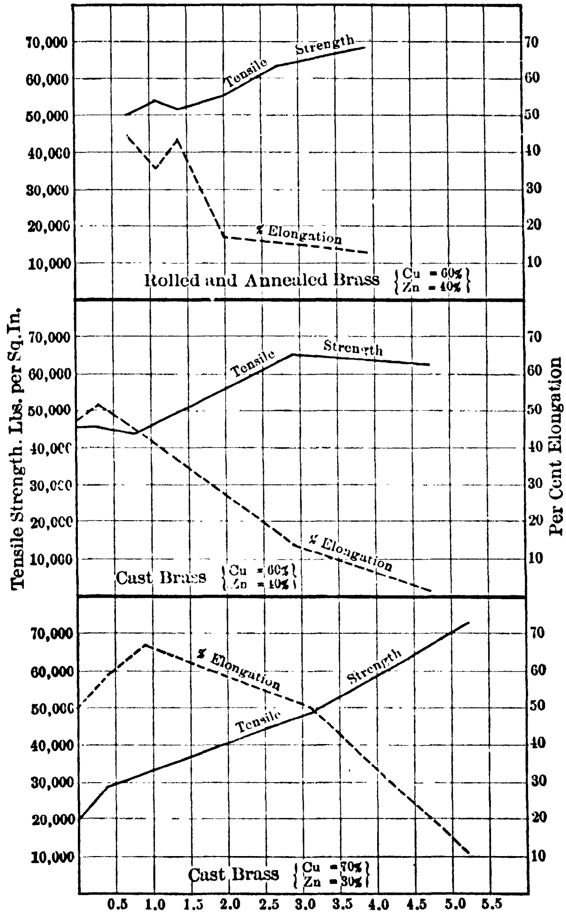

FIG. 68 — Effect of Aluminum on Tensile Properties of Brass. (Guillet.)

Copper-zinc-manganese Alloys. Manganese Bronze. One of the most valuable copper-zinc alloys is the so-called "manganese bronze." The presence of small amounts of manganese in the finished alloy is beneficial to strength in a measure, but the commercial alloy known by this name is simply a brass with which a small amount of manganese, in the form of ferromanganese, or manganese-copper produced in the electric furnace, has been incorporated while molten for the sake of the important deoxidizing effect which the manganese exerts. The resultant alloy usually contains no manganese, or only a trace, because it has been oxidized out and fluxed off.

The range of composition of various brands of manganese bronze is quite wide, and the properties of the metal vary accordingly. A soft grade is made especially for use in situations where it must withstand shock and vibration. This metal has a tensile strength of about 60,000 pounds per square inch with an elongation of 40 to 50 per cent in 2 inches. A very hard grade is made which has a tensile strength of 90,000 to 100,000 pounds per square inch with elongation of 15 to 25 per cent.

The average grade of manganese bronze shows approximately the properties listed in Table XVIII.

TABLE XVIII

MECHANICAL PROPERTIES OF MANGANESE BRONZE

	Tension			Compression	
	Elastic Limit, lb. per sq. in.	Tensile Strength, lb. per sq. in.	Elongation in 2 in., per cent	Elastic Limit, lb. per sq. in.	Compressive Strength, lb. per sq. in.
Cast manganese bronze	30,000 to 40,000	70,000 to 80,000	20 to 35	35,000 to 40,000	90,000 to 100,000
Rolled or forged manganese bronze	40,000 to 50,000	80,000 to 110,000	15 to 30	50,000 to 60,000	130,000 to 150,000

Probably no metal or alloy possessing equal strength and toughness can be cast in intricate forms so successfully as manganese bronze. In addition, it is particularly resistant to corrosion by sea water and is proof against attack by dilute acids. Manganese bronze is very commonly used for steamship propellers and other ship fittings, for piston rods, shafts, axles, and for many kinds of castings, forgings, etc., used in general machine, locomotive, and automobile construction.

Copper-zinc-iron Alloys. Two brass alloys containing iron have been commonly used. *Sterro metal* contains about 60 per cent of copper, 38 to 38.5 per cent of zinc, and 1.5 to 2 per cent of iron. *Delta metal* varies in composition, but usually contains about 55 per cent of copper, 41 per cent of zinc, 3 per cent of iron, and 1 per cent of manganese, phosphorus, and other elements. These metals, particularly the delta metal, possess a considerably higher strength and better working qualities than the brass would possess without the iron addition. They are also more resistant to corrosion. They possess, to a lesser extent, the characteristic properties of manganese bronze and aluminum brass, and have been adopted for the same class of uses, principally on marine construction.

223. Copper-aluminum Alloys. The alloys of copper and aluminum are the most valuable of the copper alloys other than the bronzes and brasses. The principal commercial alloy of copper and aluminum is the so-called aluminum bronze, which usually contains from 90 to 95 per cent of copper and 5 to 10 per cent of aluminum and no tin.

The addition of aluminum to copper causes a gradual raising of the tensile strength and yield point, and a rapid increase in ductility, until about 7.35 per cent of aluminum is present. Further additions cause an increase in the strength and yield point, accompanied by a rapid decrease in ductility, until an alloy of maximum strength (60,000 to 74,000 pounds per square inch for castings) is reached with about 10 per cent of aluminum. With additions of aluminum beyond 10 per cent, the strength falls off rapidly and the ductility becomes very small.

Most of the aluminum bronzes work well in the foundry and may easily be rolled below a bright red heat, forged at a low red heat, or drawn into bars, shapes, sheets, tubes, wires, etc. Aluminum bronze has fatigue resistance close to that of steel. The metal is highly resistant to corrosion and has, therefore, been used for ship fittings and propeller blades. On account of its excellent resistance to corrosive attack of acid solutions it is valuable for pickling apparatus, pumps for acids, pipes, vats, etc. Aluminum bronze is attacked, however, by ammonium solutions. In ordinary machine construction and in automobile construction it has found many special applications, and, because of the peculiar smooth surface which it acquires, it has been found to be an excellent anti-friction metal. One of the disadvantages of aluminum bronze is the difficulty in producing an alloy of uniform quality. Also the metal is difficult to weld.

224. Beryllium-copper Alloy. Beryllium-copper alloy contains a small percentage of beryllium alloyed with copper. An alloy containing 2.25 per cent beryllium is in most general use at present. The addition of beryllium to copper produces effects comparable to those of carbon on iron. Like steel, beryllium copper is hardenable by appropriate heat treatment, and the properties thus produced may extend over a wide range.

Beryllium metal, also called glucinum, has the low specific gravity of 1.84, as compared with 1.74 for magnesium, but its melting temperature of 1285° C. (2345° F.) is much higher than that of either magnesium or aluminum. It is a stable light-weight metal with a high melting point. Its coefficient of expansion and calculated modulus of elasticity are very close to the values for iron. Although beryllium ore is fairly abundant, the amount of beryllium metal produced has been small on account of difficulties in reducing.

Heat Treatment. To harden a 2.25 per cent beryllium-copper alloy it is heated first to a dull red heat and quenched rapidly. This quenching treatment renders the alloy comparatively soft and machinable, but, when it is reheated to a low temperature, a Brinell hardness of 385 may be attained with a tensile strength of about 200,000 pounds per square inch.

Properties and Uses. An outstanding quality of beryllium-copper alloys is their high endurance limit in fatigue. Values of endurance limit are reported to vary from 35,000 to 44,000 pounds per square inch, which compare favorably with heat-treated low-carbon steels. The unique feature is their ability to maintain this high endurance limit under corrosive conditions and at temperatures from 150 to 200° C. (302 to 392° F.).

Owing to its non-sparking characteristics, beryllium-copper alloy is utilized in manufacturing chisels and hammers for use under conditions where sparks might cause an explosion.

Beryllium-nickel alloy has heat-treating properties similar to those of beryllium-copper alloy. The addition of beryllium in small quantities to aluminum hardens the alloy and improves its machining properties.

The development of more novel and useful alloys of beryllium is quite probable, and experimental work on various new alloys will be increased as more beryllium is produced with accompanying price reduction.

ALLOYS OF ALUMINUM

225. General. The rapid increase in the number of automobiles and especially the demand for light alloys for airplane construction have brought aluminum alloys into such prominence that they are approaching the copper alloys in importance in engineering practice.

226. Aluminum-zinc Alloys. Aluminum-zinc alloys are the cheapest of the light alloys. Proportions up to about 25 per cent of zinc are used, the most ductile and malleable alloys containing less than 15 per cent of zinc, while those containing higher zinc contents are still useful in castings that permit of a certain degree of brittleness. These alloys are readily made, are harder and more fusible than aluminum, and are still very light.

Fig. 69 shows that all the alloys containing more than about 15 per cent of zinc are non-ductile and very brittle, and that even when ductility is unimportant no gain in strength, or at least in yield point, is obtained by increasing the zinc content beyond about 30 per cent. The beneficial effect of hot- and cold-working of these alloys is shown in Fig. 70.

227. Aluminum-copper Alloys. Copper is one of the most common hardening agents in aluminum alloys, the amount in binary alloys rarely exceeding about 6 or possibly 8 per cent. The copper raises the strength and the yield point considerably, but causes a rapid loss of ductility.

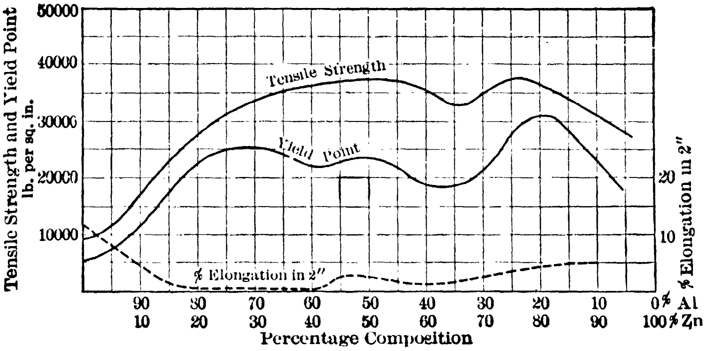

FIG. 69.—Tensile Properties of Aluminum-zinc Sand Castings. (Alloys Research Committee.)

The properties of this series of alloys have also been studied by the Alloys Research Committee, and a portion of their report is summarized in Fig. 71. A comparison of this diagram with the diagrams of Figs. 69 and 70 shows that the aluminum-copper alloys are considerably inferior to the aluminum-zinc alloys in strength, but greatly excel them in ductility. The yield point is not as high in the copper alloys as in the zinc alloys.

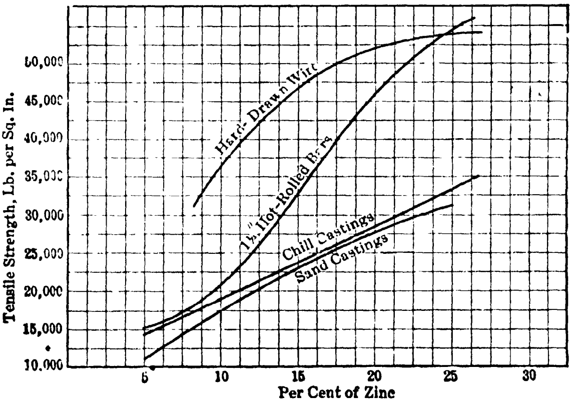

FIG. 70.—Effect of Mechanical Work on the Tensile Strength of Aluminum-zinc Alloys.

The most widely used of the casting alloys is that already mentioned as containing about 92 per cent aluminum and 8 per cent copper. This is commonly known as No. 12 alloy or as the Society of Automotive Engineers (S.A.E.) No. 30, and has an extended use in the production of various automobile and airplane parts, crankcases, camshaft housings, bodies, and, with certain slight modifications, in pistons. Many of the modern alloys of this type also contain from 0.5 to 2 per cent of iron The aluminum alloy has the advantage of lightness and high heat conductivity and for the latter reason is especially valuable in airplane construction where cooling requirements are severe. No. 12 alloy has, however, the comparatively high coefficient of thermal conductivity of 0.391 as compared with 0.147 for cast iron. The alloy is used to a large extent in the making of die-castings. The physical properties vary slightly with the conditions but are approximately as follows:

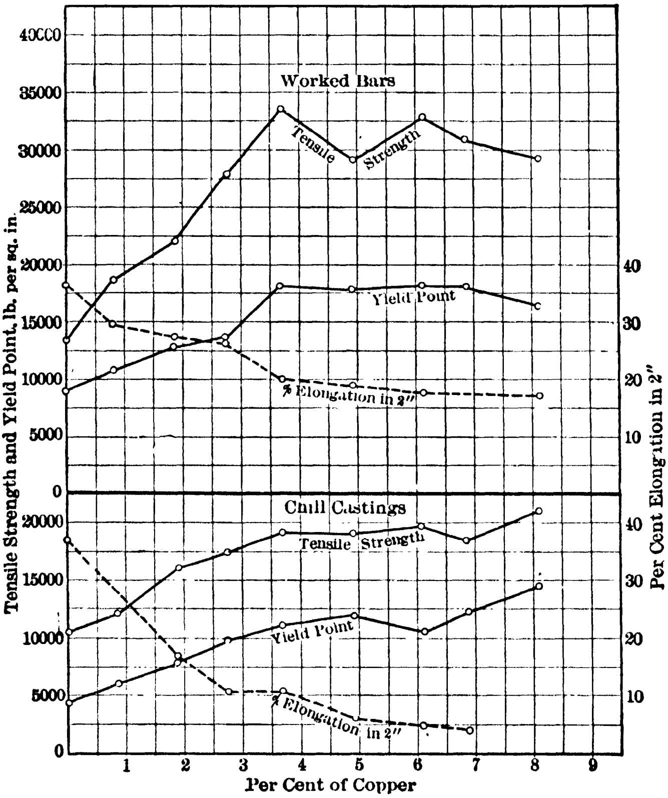

Fig. 71.—Tensile Properties of Aluminum-copper Alloys. (Alloys Research Committee.)

	Sand-cast	Die-cast
Tensile strength, lb. per sq. in.	20,000	25,000
Elastic limit, lb. per sq. in.	13,000	13,000
Elongation in 2 in., per cent	1.7	3.1
Specific gravity	2.84	2.8

British practice favors the addition of small amounts of tin (up to 2 per cent) to the aluminum-copper alloy for piston manufacture, and alloys containing decreased quantities of copper with an addition of 2 to 15 per cent of zinc are also used.

228. Aluminum-copper-zinc Alloys. Various alloys of this type contain from 9 to 27 per cent of zinc and 3 to 5 per cent of copper. The Alloys Research Committee found the alloy containing about 25 per cent of zinc and 3 per cent of copper to possess quite valuable properties. When cast in sand or in chills it showed a tensile strength of 36,500 and 40,400 pounds per square inch, respectively, but was almost absolutely non-ductile. When hot-rolled, however, it developed a tensile strength of more than 60,000 pounds per square inch with a yield point of about 44,000 pounds per square inch, and an elongation of about 16.5 per cent. It is used for crankcases in aircraft engines.

229. Aluminum-silicon Alloys. Work on these alloys has been done at various times since 1856, but only since 1921 have they attracted the attention of manufacturers. An alloy introduced by A. Pacz under the trade name "Alpax" is being used to a considerable extent because of certain valuable properties. It contains from 5 to 14 per cent of silicon and may be made in two forms: (1) "normal," in which the metals are melted in the usual way; and (2) "modified," in which the normal alloys are treated with metallic sodium or potassium or fluoride of sodium or potassium. The tensile strength of the normal alloy varies from 18,000 pounds per square inch to 21,000 pounds per square inch, depending on the proportions of the alloying metals, and in the modified form the strength is from 25,000 to 30,000 pounds per square inch with corresponding elongations of 12 to 8 per cent. The yield points of these alloys are low, but they are markedly resistant to corrosion, and, because of their low shrinkage as compared with the aluminum-copper alloys, they give excellent castings. The most common of these alloys is the 5 per cent alloy not modified.

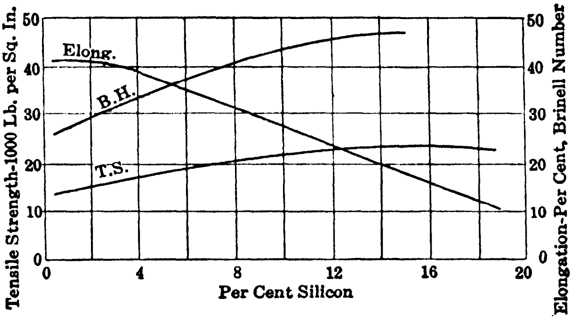

FIG. 72.—Effect of Silicon on the Properties of Aluminum.

The effect of silicon on the tensile strength, ductility, and hardness of aluminum is shown in Fig. 72.

230. Duralumin. The most interesting of the aluminum alloys, and the ones that are most common for rolling and drawing, are those developed from duralumin and sold under various trade names. Duralumin has remarkable properties that are not associated with any common alloy. An average analysis gives:

Copper,	3.5–4.6 per cent	Manganese,	0.5–1.0 per cent
Magnesium,	0.5–1.0 per cent	Aluminum,	remainder

Immediately after rolling, the metal has a tensile strength of 30,000 to 35,000 pounds per square inch with an elongation of about 4 per cent in 2 inches. If it is then heated to about 510° C. (950° F.) and suddenly cooled (quenched), it is soft and malleable for a very short time but soon begins to undergo a marked change in properties due to "aging."

Duralumin may be aged, after quenching, either at room temperature for several days or at higher temperatures, 100°–200° C. (212°–392° F.), for much shorter periods, often only a few hours. The tensile properties will be practically the same by either treatment. Aging will increase the tensile strength to 50,000 or 60,000 pounds per square inch and the elongation to about 20 per cent in 2 inches. The alloy in the rolled and aged condition resists fatigue stresses well and is quite resistant to corrosion. The normally aged material resists corrosion much better than metal that has been artificially aged. It is much used in aircraft construction and under conditions which need a material with the lightness of aluminum and almost the strength of some classes of steel. Duralumin is the alloy which has made possible the building of the large dirigibles of the Zeppelin type and in the form of rolled sheet has been used in the construction of the all-metal airplane. The tensile properties are given in Table XIX.

TABLE XIX

TENSILE PROPERTIES OF DURALUMIN

Form	Tensile Strength, lb. per sq. in.	Yield Point, lb. per sq. in.	Elongation in 2 in., per cent
Sheet	55,000–65,000	25,000	15
Tubes	55,000	35,000	15
Tubes	50,000	25,000	20
Bars ¼ to 1 in.	55,000–65,000	25,000	15
Bars 1 to 2 in.	50,000	25,000	15
Bars 2 in. and above	45,000	20,000	15

The effect of aging on the properties of heat-treated specimens machined from duralumin rod stock, of the composition copper 4.0 per cent, magnesium 0.5 per cent, manganese 0.6 per cent, chromium 0.1 per cent, and aluminum 94.8 per cent, is shown in Fig. 73.

One of the objections to duralumin has been its susceptibility to failure as a result of intercrystalline corrosion. A recently developed method known as the "Alclad" process has proved effective in remedying this fault. The metal "Alclad" is sheet duralumin to which aluminum of the highest purity is bonded on the two faces. The resulting structure is shown in the photomicrograph, Fig. 74. The layers of aluminum are

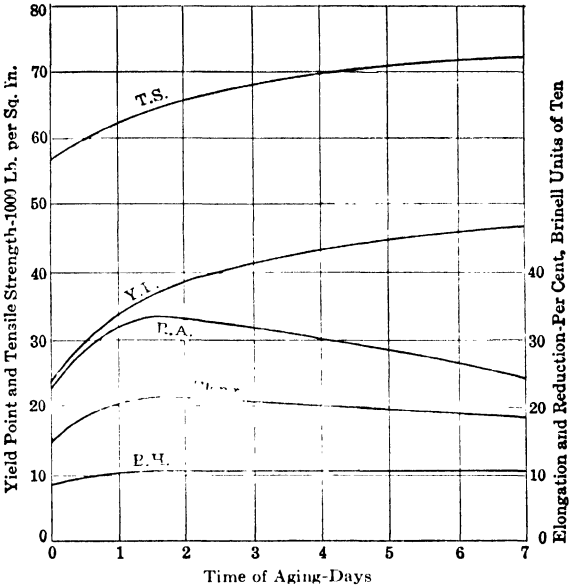

Fig. 73.—Effect of Aging upon the Properties of Duralumin.

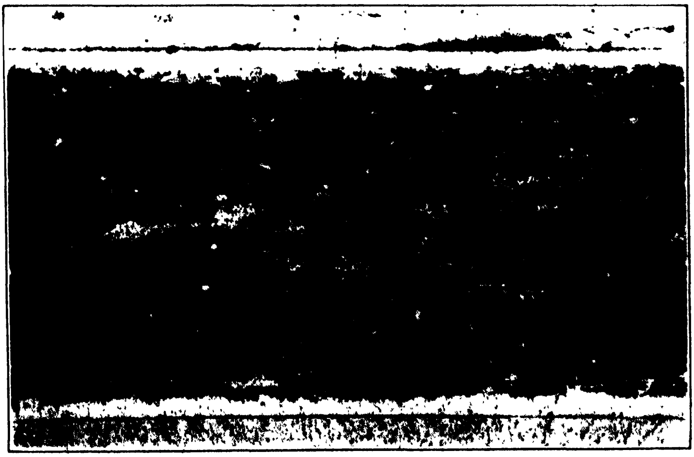

Fig. 74.—Alclad 100×.

so thin that the loss in tensile strength is only about 1 per cent while the corrosion resistance is enormously increased. This is the material that is used in the gas bags of large dirigibles.

231. Minor Alloys of Aluminum. *Aluminum-magnesium Alloys.* The alloy of aluminum and magnesium possessing the most valuable properties is one containing less than 2 per cent (usually about 1.6 per cent) of magnesium. This alloy is slightly lighter than pure aluminum, but shows a tensile strength of 25,000 to 40,000 pounds per square inch when cast and rapidly cooled or when rolled without annealing. The commercial alloy of aluminum and magnesium usually contains small percentages of copper, nickel, tin, or lead.

Alloys of aluminum with nickel, tin, manganese, tungsten, chromium, titanium, silver, and antimony have been made commercially, but none possess such valuable distinctive properties as to have won for them an important place among the light alloys.

"Y" alloy, containing copper 3.5–4.5 per cent, nickel 1.8–2.3 per cent, magnesium 1.2–1.7 per cent, and the remainder aluminum, has been used considerably as a casting alloy especially for the pistons of aircraft engines. When cast it has a tensile strength of only 28,000 pounds per square inch, but when rolled, quenched, and aged shows 54,000 pounds per square inch with a ductility of about 20 per cent in 2 inches. Y alloy holds its strength over long periods of time.

"E" alloy contains approximately copper 2.5 per cent, zinc 20 per cent, magnesium 0.5 per cent, manganese 0.5 per cent, silicon 0.20 per cent, and the remainder aluminum. When rolled and annealed with no aging, it develops a tensile strength of 56,000 pounds per square inch and an elongation of 20 per cent in 2 inches; when heated to 400° C., quenched, and aged, it shows values of 87,000 pounds per square inch tensile strength and 11 per cent elongation in 2 inches. The addition of a high percentage of zinc increases the specific gravity.

232. Aluminum-coated Iron and Steel. Aluminum-coated iron and steel are now being produced in the form of wires, rods, and sheets under the trade name "Alplate." The essential feature of the process is to subject ferrous metal to the action of a reducing gas such as hydrogen before placing it into the aluminum bath. This treatment removes oxygen and causes reduction of oxides on the surface of the ferrous metal, and also charges the surface with enough of the reducing gas to insure a satisfactory union with aluminum at the time of immersion. It is claimed that this product can be subjected to metal working without cracking or detachment of the coating. The material is corrosion-resistant and fireproof up to 1000° C. (1832° F.).

ALLOYS OF MAGNESIUM

233. Alloys of Magnesium. The addition of aluminum to magnesium up to about 9 per cent produces a solid solution called the "delta" phase which has much greater strength and somewhat greater ductility than magnesium. The low specific gravity of 1.8 of this alloy is of great importance. Owing to its light weight it is employed in airplane construction for structural shapes, chair frames, engine parts such as cast pistons and crankcases, and forged propellers. It is also used to some extent in automobile construction.

Casting alloys contain from 6 to 8.5 per cent aluminum and 0.2 to 0.4 per cent manganese. The addition of manganese improves resistance against corrosion by salt water and salt-water atmosphere and also makes the metal capable of being welded. For molding in sand an alloy of 8.5 per cent aluminum and 0.4 per cent zinc is suitable. For press work, 8.5 per cent aluminum content is quite good. For die-castings an aluminum content of 9 to 11 per cent is specified by the American Society for Testing Materials in order to give greater fluidity than is possessed by alloys of lower aluminum percentage. Magnesium alloy containing 12 per cent aluminum has increased strength and hardness when heat-treated but is too brittle for many purposes.

The physical properties of magnesium alloy containing 8 per cent aluminum and 0.3 per cent manganese may be somewhat variable but when cast it shows an average tensile strength of about 25,000 pounds per square inch, a compressive strength of about 45,000 pounds per square inch, an elongation of about 9 per cent in 2 inches, and a Brinell hardness of 55. Both rolled and forged alloys have greater strength.

Magnesium alloys have certain disadvantages as compared with aluminum alloys. Cold-shaping at room temperature of magnesium alloys must be carefully controlled, but, if the alloy is heated to 225° C. (437° F.), molding and shaping are made much easier. The hexagonal space lattice of the crystals does not permit rapid change of shape as obtained by means of drop hammers or spindle presses, but the hydraulic press is of advantage in shaping since pressure can be applied slowly. Rolling should be carried out only at a temperature of at least 300° C. (572° F.).

The thermal conductivity of magnesium-aluminum alloys is about 0.200 (gram-cal. per sec. per cm.-cube per degree C.), which is less than for magnesium or aluminum, but greater than for cast iron, whose value is 0.147. Its thermal coefficient of expansion is 0.000029 per degree C. as compared to 0.000011 for cast iron. Its melting point is about 620° C. (1148° F.), depending on composition. Magnesium alloys in a finely divided state will burn, but large sections in the solid state are not easily ignited.

Dow metal is the commercial name of a magnesium-aluminum alloy. *Electron metal* is the commercial name applied to a magnesium alloy containing about 4 per cent zinc and small percentages of copper, iron, and silicon. It has a tensile strength of about 40,000 pounds per square inch and an elongation in 2 inches of about 18 per cent. Its applications are similar to those of magnesium-aluminum alloys.

ALLOYS OF NICKEL

234. Monel Metal. An important alloy of nickel with copper and small percentages of other elements is the so-called natural alloy, Monel metal, obtained by the direct smelting of a Canadian ore. The process consists of calcination of copper-nickel sulfide ore, reduction of the corresponding oxide with charcoal in acid open-hearth furnaces, and refining in basic electric furnaces. The regular Monel metal, designated as B Monel metal, is a solid solution; its chemical and mechanical properties are given in Table XX. It is of value chiefly because of its great resistance to corrosive liquids, acids, pickling solutions, mine waters, and the like, and because of the fact that it retains its physical properties at temperatures considerably higher than most of the common alloys, both non-ferrous and steel. The effect of temperature on the tensile properties of B Monel metal is shown in Fig. 75.

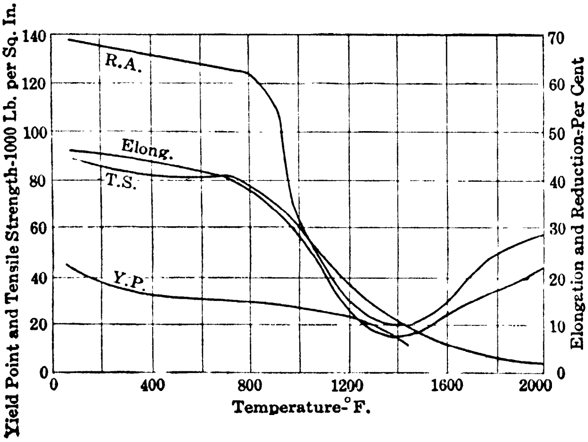

FIG. 75.—Properties of B Monel Metal at High Temperatures.

R Monel metal is a special alloy containing a small amount of sulfur to give free-machining properties and is adapted to the manufacture of automatic screw machine products.

K Monel metal is a special alloy produced by the addition of 2 to 4 per cent of aluminum to Monel metal. It has age-hardening properties and is non-magnetic. It is used for pump rods and propeller shafts. The chemical and mechanical properties of R and K Monel metals are given in Table XX.

Inconel Metal. This nickel-chromium-iron alloy has corrosion resistance to tarnishing and is used in the food industries. It is non-magnetic, and because of its freedom from scaling and intercrystalline attack it is suitable for use at elevated temperatures. Its properties are also given in Table XX.

TABLE XX

Chemical and Mechanical Properties of Monel Metal and Inconel Metal[1]

	B Monel, Hot-rolled	B Monel, Cold-drawn, 24% Reduction, Stress Relieved	B Monel, Cold-drawn, Annealed 1450° F., 3 hr.	R Monel, Hot-rolled	K Monel, Hot-rolled	K Monel, Cold-drawn, Age-hardened 10 hr. at 1050° F.	Inconel, Hot-rolled
Nickel, per cent.	66.7	66.7	66.7	66.6	65.0	65.0	81.0
Copper, per cent.	31.3	31.3	31.3	31.1	30.1	30.1	0.1
Aluminum, per cent.	. . . . .	. . . . . .	. . . . . .	. . . . .	3.2	3.2	. . . . .
Chromium, per cent.	. . . . .	. . . . . .	. . . . . .	. . . . .	. . . . .	. . . . . .	13.0
Iron, per cent. . .	0.8	0.8	0.8	1.1	0.8	0.8	5.5
Manganese, per cent.	0.9	0.9	0.9	1.0	0.5	0.5	0.1
Sulfur, per cent. .	0.007	0.007	0.007	0.041	0.005	0.005	0.008
Tensile strength, lb. per sq. in. . .	83,750	97,250	78,350	75,600	99,900	157,650	91,150
Yield strength, lb. per sq. in. (0.2% offset). .	40,650	86,650	33,350	35,650	47,000	119,650	47,000
Elongation in 2 in., per cent. . .	39.5	27.0	44.0	39.5	42.5	22.0	42.0
Reduction of area, per cent.	67.5	66.4	65.9	68.9	63.7	37.5	66.0
Compression yield strength, lb. per sq. in. (0.2% offset). .	38,050	80,750	28,250	33,500	40,350	121,250	41,950
Brinell hardness, (3000-kg. load)	145	199	123	121	163	329	159
Charpy impact, ft-lb.	232	151	206	187	170	42	191

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[1] C. F. Catlin and W. A. Mudge: *Proceedings A.S.T.M.*, v. 38, Part II, 1938.

235. Nickel Silver. Nickel silver or German silver is brass to which nickel has been added. It is valuable chiefly because of its silvery white color and its resistance to corrosion. Other metals are sometimes added in small amounts.

The typical compositions of nickel silver are nickel 5 to 30 per cent, zinc 10 to 35 per cent, and copper 50 to 80 per cent. The whitest metal is obtained with about 25 to 30 per cent of nickel and 20 to 25 per cent of zinc, but, since the nickel is the most expensive constituent, its proportion is often cut down. The alloy containing 30 per cent of zinc and about 18 per cent of nickel is quite white, makes smooth, sound castings, and is best from the standpoint of malleability and toughness. Aluminum in amounts up to about 25 per cent makes the metal more fluid while molten and is therefore desirable in castings. It also toughens the cooled casting. Iron hardens the metal, and makes it whiter when present in amounts not exceeding 1 to 2 per cent. Tungsten up to 1 or 2 per cent is also occasionally added to form an alloy called *platinoid* which has unusually high electrical resistance, and is used for electrical purposes.

Nickel silver is principally used in the making of domestic utensils, tableware, decorative objects, physical and scientific instruments, coinage, etc.

DIE-CASTING ALLOYS

236. Die-castings. Die-casting consists of forming one casting after another under pressure by means of a permanent mold. Die-castings can be formed sufficiently close to dimensions so that for many purposes machining is not required; they can be polished or chromium-plated to improve the appearance. Die-castings are used a great deal in automobile construction and for small machine parts. Alloys of zinc are most common for die-casting, but alloys of aluminum, magnesium, and copper are also suitable for the purpose.

237. Zinc Die-casting Alloys. A typical composition is aluminum, 4 per cent; copper, 1 to 3 per cent; small amounts of iron, magnesium, lead, cadmium, and tin, and the remainder zinc. This alloy has greater fluidity than zinc and can be die-cast into complicated shapes and thin sections. The physical properties are also improved, the tensile strength being approximately 44,000 pounds per square inch, compressive strength about 90,000 pounds per square inch, elongation in 2 inches about 5 per cent, and Brinell hardness about 76. The presence of small quantities of lead in zinc in a short time brings about a change in physical and dimensional stability, but this tendency is corrected by using an antidote of 1 to 3 per cent of copper. Magnesium is also used as an antidote but does not give as good strength or hardness as copper.

238. Aluminum Die-casting Alloys. The American Society for Testing Materials specifications cover eight aluminum-base alloys of different compositions for die-casting. Table XXI states the composition and approximate mechanical properties of these alloys.

TABLE XXI

COMPOSITION AND MECHANICAL PROPERTIES OF ALUMINUM-BASE DIE-CASTING ALLOYS

Alloy No.	Desired Composition, per cent				Iron,[1] Maximum Per Cent	Tensile Strength, lb. per sq. in.	Elongation in 2 in., per cent	Charpy Impact on Square Specimens, ft-lb.
	Aluminum	Copper	Silicon	Nickel				
IV	95	.....	5	.....	2.0	29,000	3.5	4.5
V	88	.....	12	.....	2.0	33,000	1.5	2.0
VI	95	2	3	.....	2.5	30,000	3.5	5.0
VII	91	4	5	.....	2.3	32,000	2.0	2.5
VIII	95.25	1.5	1	2.25	2.5	29,000	4.0	4.5
IX	90.25	4	1.75	4	1.8	31,000	1.5	2.0
XI	90	2	8	.....	2.0	32,000	1.7	3.0
XII	91	7	2	.....	2.3	34,000	1.6	3.2

[1] Iron contributes to hardness in all these alloys. Maximum limits are also given for zinc, manganese, magnesium, and tin.

239. Magnesium Die-casting Alloys. The American Society for Testing Materials specifications refer to one alloy No. 12 whose composition is required to meet the following limits: aluminum 9 to 11 per cent, a minimum of 0.10 per cent manganese, and a maximum of 1.0 per cent silicon, 0.05 per cent copper, 0.03 per cent nickel, and 0.5 per cent other ingredients. The approximate tensile strength is 26,000 to 30,000 pounds per square inch, elongation in 2 inches is 1 to 3 per cent, and Charpy impact is 1 to 3 foot-pounds.

240. Brass Die-castings. It has been found possible to force brass into die cavities by means of high pressure at a temperature somewhat below the melting point. The copper content of brass die-castings ranges from 57 to 81.5 per cent, but brass having a composition of 60 per cent copper and 40 per cent zinc with the comparatively low melting point of 904° C. (1655° F.) is generally used since it is less severe on dies than brasses of higher copper content and yet has good physical properties. Brass die-castings have good strength and corrosion resistance. They have mechanical properties superior to those of brass sand castings for the same alloy owing to a finer grain size, and have better surface finish and soundness, and greater dimensional accuracy. Brass sand castings which require little machining are cheaper, however. Forgings have better machinability and soundness than die-castings. Where zinc die-castings have proved satisfactory, it is doubtful that brass die-castings can overcome their advantages and replace them.

BEARING METALS AND FUSIBLE ALLOYS

241. Special Bearing or Anti-friction Metals. The bearing bronzes and the lead-antimony bearing metals have been already considered. Aside from the bearing bronzes, the best-known bearing metals are those composed of tin, copper, and antimony, which are called *babbitt metal.* The composition of this alloy is extremely variable, but the usual limits are tin 80 to 90 per cent, copper 3 to 10 per cent, and antimony 8 to 12 per cent. The quantity of antimony should always exceed the amount of copper in order to prevent brittleness. The ultimate constitution of babbitt metals appears to be that of a ground mass of soft tin with hard crystals of a copper-antimony compound and a tin-antimony compound scattered through it. The hard particles carry the load and resist wear, while the soft ground mass allows the metal to adjust itself to the surface of the shaft and equalize the bearing pressure.

Alloys of lead, tin, and antimony have been considerably used as bearing metals, the best compositions being those containing 10 to 15 per cent of antimony, 10 to 20 per cent of tin, and the balance lead.

Alloys of lead, copper, and antimony have occasionally been used as bearing metals where heavy loads are encountered. A typical composition is lead 65 per cent, copper 10 per cent, and antimony 25 per cent.

Alloys of zinc, tin, and antimony, and *alloys of lead, tin, and bismuth* have been used as bearing metals, but their general application has been very limited on account of a tendency toward fragility of the first group, and the high cost of bismuth in the second.

Alloys of lead with barium or with *calcium* have recently been quite successful as bearing alloys.

The American Society for Testing Materials has published tentative composition specifications for a large list of white metals or babbitts. The Society of Automotive Engineers has also published specifications for five babbitts which, it is believed, will meet all ordinary needs, and from which the summary in Table XXII has been made.

TABLE XXII

S.A.E. BABBITT METALS

No.	Approximate Composition			
	Sn	Cu	Sb	Pb
10	90.0	5.0	5.0	....
11	87.0	6.0	7.0	....
12	60.0	3.0	11.0	26.0
13	5.0	0.5	9.5	85.0
14	9.5	0.5	15.0	75 0

Alloy 10 is a very fluid babbitt suitable for thin linings or bronze-backed bearings. Alloy 11 is a rather hard babbitt which may be used under heavy pressures. It has very little "wiping" tendency. Alloy 12 is a medium-quality metal suitable for moderate conditions, and 13 and 14 are comparatively cheap babbitts to be used only under light loads in large bearings. All the above can be die-cast.

Fig. 76 shows the structure of typical babbitt metals.

FIG. 76.—Structure of Typical Babbitt Metals 100×.

242. Alloys of Low Fusibility. Alloys that fuse at very low temperatures are used in the manufacture of fusible plugs for automatic sprinkler systems, etc. These alloys always contain bismuth, lead, and tin, often cadmium, and occasionally mercury. A list of fusible alloys covering a fairly wide range of low fusibility temperatures is presented in Table XXIII.

TABLE XXIII

FUSIBLE ALLOYS

Alloy	Composition				Temp. of Fusion	
	Bi	Pb	Sn	Cd	° C.	° F.
Lipowitz'	50.0	26.7	13.3	10.0	60.0	140.0
Wood's	50.0	25.0	12.5	12.5	68.0	154.4
Guthrie's	47.4	19.4	20.0	13.2	74.0	165.2
D'Arcet's	50.0	25.0	25.0	....	93.0	199.4
Newton's	50.0	31.2	18.8	....	95.0	205.0
Rose's	50.0	28.0	22.0	....	100.0	212.0

QUESTIONS

1. Name the essential steps in extracting copper from sulfide ores.

2. Discuss briefly the relation between the strength of copper and the mechanical treatment to which it has been subjected.

3. Discuss the corrosion resistance of copper.

4. What are the chief uses of copper?

5. Explain how zinc spelter protects galvanized iron from corrosion.

6. State the principal uses of zinc.

7. What are the commercial forms of lead?

8. What are the main properties of lead usually taken into account? What is the significance of the tensile strength of lead? Why?

9. What are the principal sources and properties of tin?

10. Describe in general the effect of cold-working upon the tensile properties of aluminum.

11. Discuss the resistance of aluminum to corrosion.

12. Compare the electrical conductivity of copper and aluminum.

13. Compare the methods of manufacturing zinc, lead, aluminum, and magnesium.

14. What are the important properties and uses of magnesium?

15. Describe the physical properties of nickel.

16. Identify the alpha phase of bronze.

17. How do the physical properties of bronze vary with increase in tin content?

18. What is the composition range for machinery bronzes?

19. What are the composition, properties, and uses of
    (*a*) Phosphor bronze.
    (*b*) Silicon bronze.
    (*c*) Manganese bronze.
    (*d*) Aluminum bronze.
    (*e*) Gun metal.

20. What is the composition of statuary bronze? What is meant by "patina"?

21. For what purpose is lead added to bronze?

22. Describe the constitution of brasses.

23. What is the composition of standard brass? How does its strength compare with that of copper and zinc? Where might it be used? Why?

24. What causes "season cracking"? How can it be remedied?

25. Compare the compositions and uses of admiralty metal, naval brass, and Muntz metal.

26. What are the principal properties of beryllium copper?

27. What is the effect of aging upon the properties of duralumin?

28. What is "Alclad"?

29. Identify "Y" alloy and "E" alloy.

30. State the composition, properties, and uses of Monel metal and nickel silver.

31. State the composition, properties, and uses of the principal alloys of magnesium. What is Dow metal?

32. Describe the composition, properties, and uses of the principal die-casting alloys.
33. What is babbitt metal, and why is it effective as a bearing metal?
34. What elements are contained in alloys of low fusibility?

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CHAPTER XI

SPECIAL ALLOY STEELS

243. Definition and Classification. An alloy steel may be defined as a steel that owes its distinctive properties chiefly to some element or elements other than carbon. *Ternary steels,* or three-part alloy steels, are those whose properties are chiefly dependent upon the presence of one element other than iron and carbon. *Quaternary steels* contain two influential elements other than iron and carbon.

All alloy steels bear names that indicate the alloying element present. The principal classes of alloy steels are those listed below:

TERNARY ALLOYS

- Nickel steel
- Silicon steel
- Copper steel
- Manganese steel
- Chromium steel
- Tungsten steel
- Molybdenum steel
- Vanadium steel

QUATERNARY ALLOYS

- Chrome-nickel steel
- Chrome-vanadium steel
- Chrome-molybdenum steel
- Chrome-tungsten steel
- Chrome-silicon steel
- Manganese-silicon steel
- Aluminum-chromium steel

The special elements may be divided into two classifications: (1) those like nickel, silicon, and copper which do *not* combine with carbon to form carbides; and (2) those like manganese, chromium, tungsten, molybdenum, and vanadium which do combine with carbon to form carbides.

In addition to the above steels, zirconium and uranium steels are manufactured, but the extent of their usefulness has not as yet been fully determined. Alloying elements such as titanium, aluminum, and vanadium are sometimes used to act as scavengers and otherwise facilitate manufacture. In such cases the alloying element is absent, or nearly so, in the final analysis, and steels so prepared are known as alloy-treated steels. Alloy steels are also manufactured which contain more than two alloying elements but, with the exception of high-speed tool steel, they are rare.

The benefit from the alloying elements and the valuable properties of an alloy steel can be obtained only by proper heat treating. As a general rule, alloy steels when untreated are little, if at all, superior to plain carbon steel. Structural nickel and silicon steels may be mentioned as exceptions.

244. S.A.E. Steel Numbering System. The Society of Automotive Engineers has developed a convenient classification of steels by means of a numeral index system which makes it possible to indicate by numerals on shop drawings and blueprints partial descriptions of the composition of the metals. The first digit indicates the type to which the steel belongs; thus "1—" indicates a carbon steel; "2—" a nickel steel; "3—" a nickel-chromium steel. The approximate percentage of carbon, expressed in hundredths of 1 per cent, is shown by the last two digits. For simple alloy steels the second digit generally indicates the approximate percentage of the predominant alloying element. Thus 1020 indicates a plain carbon steel of approximately 0.20 per cent carbon; 2350 indicates a nickel steel of 3.25–3.75 per cent nickel and 0.45–0.55 per cent carbon; 71360 indicates a tungsten steel of about 13 per cent tungsten (12 to 15) and 0.50–0.70 per cent carbon. Table XXIV, giving the basic numerals for the various types of S.A.E. steel, is taken from the S.A.E. Handbook, 1937 edition.

TABLE XXIV

S.A.E. NUMERAL INDEX SYSTEM FOR STEELS

Type of Steel	Numerals (and Digits)
Carbon Steels	1xxx
Plain carbon	10xx
Free cutting (screw stock)	11xx
Free cutting, manganese	X13xx
High-manganese Steels	T13xx
Nickel Steels	2xxx
0.50 per cent nickel	20xx
1.50 per cent nickel	21xx
3.50 per cent nickel	23xx
5.00 per cent nickel	25xx
Nickel-chromium Steels	3xxx
1.25 per cent nickel, 0.60 per cent chromium	31xx
1.75 per cent nickel, 1.00 per cent chromium	32xx
3.50 per cent nickel, 1.50 per cent chromium	33xx
3.00 per cent nickel, 0.80 per cent chromium	34xx
Corrosion and heat-resisting steels	30xxx
Molybdenum Steels	4xxx
Chromium	41xx
Chromium-nickel	43xx
Nickel	46xx and 48xx
Chromium Steels	5xxx
Low-chromium	51xx
Medium-chromium	52xxx
Corrosion and heat-resisting	51xxx
Chromium-vanadium Steels	6xxx
Tungsten Steels	7xxx and 7xxxx
Silicon-manganese Steels	9xxx

TERNARY STEELS

245. Nickel Steel. The first alloy steel to become important was probably that containing nickel, which was added, originally, to give strength and toughness. Nickel steel usually contains between 2 and 5 per cent of nickel with 0.10 to 0.50 per cent of carbon. This class of alloy steel combines great tensile strength and hardness with a high elastic ratio, good ductility, and relatively high resistance to corrosion. In addition to this class, certain special high-nickel steels are notable because of their remarkably low coefficients of expansion, their resistance to corrosion, and their electrical or magnetic properties.

Critical Ranges. The presence of nickel in varying amounts has an important effect upon the position of the critical points in cooling: 3.8 per cent nickel lowers the critical points about 75° C. (167° F.), and as the nickel is increased this effect becomes more pronounced until with about 25 per cent of nickel the critical range is below ordinary atmospheric temperature. This effect of nickel makes it possible to have a steel which, without quenching, may be pearlitic, martensitic, or austenitic, dependent upon the nickel-carbon ratio, Fig. 77.

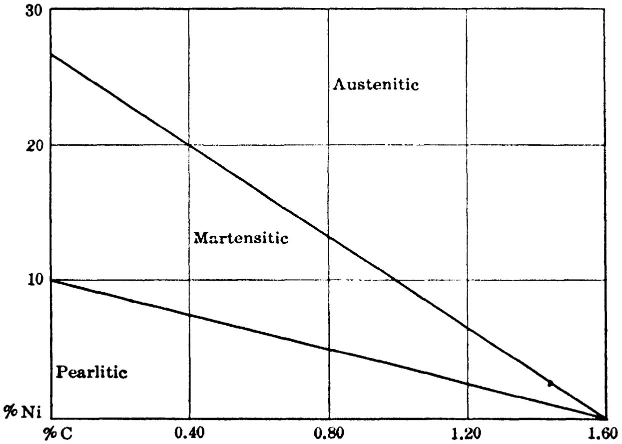


Fig. 77.—Influence of the Nickel-carbon Content upon the Structure of Nickel Steel as Cast. (Guillet.)

Tensile Properties. The general effect of a small amount of nickel upon the tensile properties of steel is to raise the ultimate strength and elastic limit without sacrificing ductility. The characteristic properties of a given nickel steel are not dependent, solely, upon the amount of nickel, however, as the carbon content and the heat treatment are also very important factors. The comparative physical properties of nickel steels with 0.25 per cent carbon are shown in Fig. 78, and the effect of heat treatment on 3½ per cent nickel steel is illustrated in Fig. 79.

In steels with less than 5 per cent nickel the tensile strength is raised, approximately, 5000 pounds per square inch for each 1 per cent of nickel.

When the nickel content exceeds 5 per cent the metal becomes hard and cannot be worked easily, hot or cold. The hardness increases as the percentage of nickel increases. The steel containing 13 per cent nickel and 0.55 per cent carbon discovered by Arnold and Read is so hard that it cannot be machined.

The tensile properties specified by the American Society for Testing Materials for structural nickel steel to contain from 3.0 to 4.0 per cent nickel are listed in Table XXV.

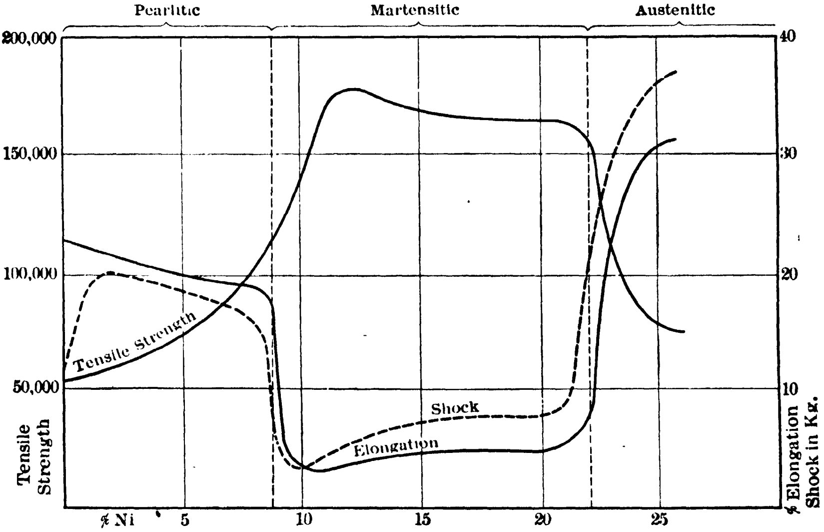


FIG. 78.—Comparative Physical Properties of Nickel Steels with 0.25 Per Cent Carbon. (Bullens.)

The carbon content for the structural rivet steel as listed above must not be greater than 0.30 per cent, and for the steels for other structural uses, not greater than 0.45 per cent.

Special Properties. Low-nickel steels corrode somewhat less readily than the carbon steels under any condition of exposure. The high-nickel steels (18 to 40 per cent nickel) offer a marked resistance to corrosion. Comparative tests conducted at the Bureau of Standards on 36 per cent nickel steel and electrolytic iron showed a loss in weight of the pure iron of nearly four times that of the high-nickel steel.

Steels containing more than 25 per cent nickel are practically non-magnetic and have high electrical resistance and permeability. An alloy

TABLE XXV

A.S.T.M. Specifications for Structural Nickel Steel

	Rivet Steel	Plates, Shapes, and Bars	Eyebars, Flats and Rollers, Unannealed	Eyebars, Flats and Pins, Annealed
Tensile strength, lb. per sq. in....	70,000 to 80,000	90,000 to 115,000	95,000 to 110,000	85,000 to 100,000
Yield point, min., lb. per sq. in....	45,000	55,000	55,000	48,000
Elongation in 8 in., min., per cent.	$\frac{1,500,000}{\text{T.S.}}$	$\frac{1,600,000}{\text{T.S.}}$	$\frac{1,500,000}{\text{T.S.}}$	20
Elongation in 2 in., min., per cent.	....	$\frac{1,700,000}{\text{T.S.}}$	16	20
Reduction of area, min., per cent.	40	30	25	30

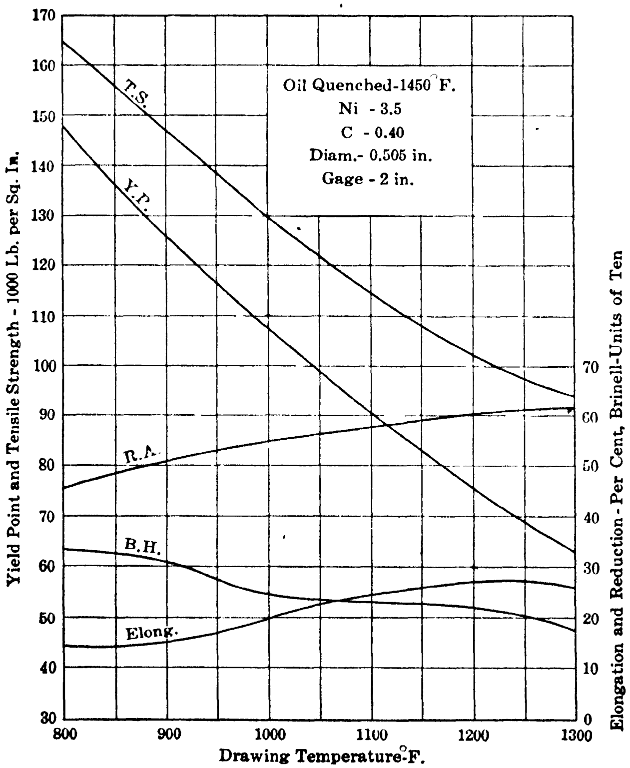


Fig. 79.—3½ Per Cent Nickel Steel, 0.4 Per Cent Carbon, Oil Quenched.

containing 80 per cent nickel and 20 per cent iron is known as *Permalloy*. Certain special nickel steels are remarkable for their low coefficient of temperature expansion; one containing 36 per cent nickel (*Invar steel*) has a coefficient approaching zero, and one containing 42 per cent nickel (*Platinite*) has at ordinary temperatures about the same coefficient as glass.

Uses. Nickel steels containing from 2 to 5 per cent nickel and 0.08 to 0.18 per cent carbon are used extensively for case-hardening because of their great toughness and resistance to shock and repeated stress. These same steels with somewhat higher carbon are used in the production of forgings. A 3½ per cent nickel steel is valuable as a structural steel because of its high elastic and endurance ratios. The use of this steel has been specified in the construction of many large bridges. All nickel steels are comparatively hard to machine.

Nickel steels containing 22 to 25 per cent of nickel are used where exposure to erosion is very severe, as in parts of pumps, salt-water connections, and spark plugs. Invar steel, Platinite, and Permalloy have been mentioned above.

Manufacture. Nickel steel is usually made by the open-hearth process, but may be made by any of the steel-making processes. Nickel is added in the form of metallic nickel, or ferronickel, charged with the rest of the stock.

246. Silicon Steel. Silicon steels resemble nickel steels in their general properties. Silicon steel of low silicon content has been used extensively in recent years for structural purposes because of its high yield point, high tensile strength, and good ductility. It has been utilized particularly in long-span bridges in order to reduce dead weight.

The average chemical and physical properties of silicon-alloy structural steel and carbon structural steel used in the towers of the George Washington Bridge are stated in Table XXVI.

TABLE XXVI

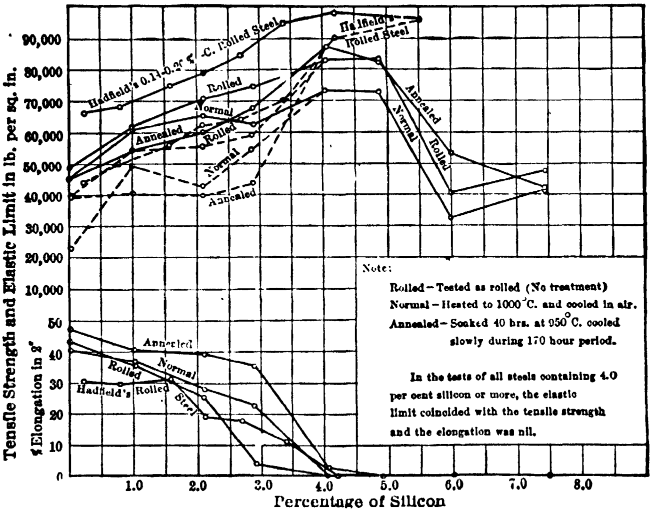
AVERAGE PROPERTIES OF SILICON AND CARBON STEELS IN TOWERS OF GEORGE WASHINGTON BRIDGE *

Property	Silicon-alloy Structural Steel	Carbon Structural Steel
Carbon, per cent	0.35	0.21
Silicon, per cent	0.27	....
Manganese, per cent	0.78	0.50
Phosphorus, per cent	0.022	0.018
Sulfur, per cent	0.037	0.037
Tensile strength, lb. per sq. in.	88,800	63,600
Yield point, lb. per sq. in.	50,800	38,200
Elongation in 8 in., per cent	22	28
Reduction of area, per cent	43	52

* H. J. Baker: *Trans. Am. Soc. Civ. Eng.*, v. 97, 1933 p. 340.

When 1 or 2 per cent of silicon is combined with 0.1 to 0.4 per cent of carbon, the resultant steel is known as Navy steel and may be classed as a high-strength structural steel resembling structural nickel steel. It is chiefly valuable because its elastic limit is very high, compared with that of an ordinary steel of equal carbon content. It is rather hard and causes some difficulty in rolling.

Hadfield's silicon steel is very valuable for use in electrical machinery. It contains 3 per cent of silicon and the smallest possible amounts of carbon, manganese, and other impurities. This steel acquires its remarkable magnetic properties (very high permeability and low core loss) only after a special heat treatment. It is heated to between 900° C. (1652° F.) and 1100° C. (2012° F.), cooled quickly to atmospheric temperatures, reheated to between 700° C. (1292° F.) and 850° C. (1562° F.), and cooled very slowly. Sometimes it is again heated and cooled very slowly from about 800° C. (1472° F.).



Note:

Rolled – Tested as rolled (No treatment)
Normal – Heated to 1000° C. and cooled in air.
Annealed – Soaked 40 hrs. at 950° C. cooled slowly during 170 hour period.

In the tests of all steels containing 4.0 per cent silicon or more, the elastic limit coincided with the tensile strength and the elongation was nil.

FIG. 80.—Tensile Properties of Silicon Steels Containing 0.04 Per Cent Carbon. (Baker.)

Tensile Properties. The tensile properties of a series of very low-carbon silicon steels are shown in Fig. 80. These curves are based upon tests made by Thomas Baker. These steels do not excel ordinary medium high-carbon steels in tensile strength or ductility, but do show a very high elastic ratio. In the presence of so small an amount of carbon, the addition of silicon seems to be beneficial to strength only in amounts not exceeding about 5 per cent, and all these steels acquire great brittleness if about 2.0 per cent silicon is exceeded.

Similar tests made by Hadfield at an earlier date with steels containing about the same range of silicon content, but having from 0.14 to 0.26 per cent carbon (Fig. 80), exhibit about the same properties as the very low-carbon steels used by Baker, except that the strength and elastic limit are slightly higher. Hadfield found forging of his steels impossible when the silicon content exceeded 5.5 per cent.

Manufacture and Uses. Silicon steel may be made in the crucible, but is more often made in the open hearth. The alloy element is added in the form of ferrosilicon. Silicon steel is used principally as a hard, high-strength, structural steel for purposes similar to those noted in discussing nickel structural steel and as thin sheet steel for the construction of the cores, pole pieces, etc., of electrical machinery.

247. Copper Steel. Copper steels containing from about 0.15 to 0.30 per cent copper have increased resistance to atmospheric corrosion as compared with ordinary carbon steels. No noticeable change in the other properties of the steels is effected by the additions of these small percentages of copper.

The committee on corrosion tests of the American Society for Testing Materials is conducting a thorough comparative test of the corrosive properties of copper-bearing and non-copper-bearing ferrous materials. The following facts and conclusions are extracted from the 1938 *Proceedings* of the Society with respect to No. 22-gauge corrugated black sheets of iron and steel:

Type Designation	No. of Groups	No. of Sheets	No. Sheets Failed	% Failed after 21 Years	No. Groups Completely Failed	Average Life of Sheets in Groups Completely Failed, in years
Copper-bearing......	17	147	44	29.9	0	....
Non-copper-bearing..	9	73	70	95.9	6	10.4 to 18.2

The observations of the committee have reached a point where it may be stated that copper-bearing metal shows a superiority in rust-resisting properties as compared with non-copper-bearing metal of substantially the same composition when subjected to atmospheric conditions.

The immersion tests carried on in various mine waters have indicated that copper has very little influence on the life of the specimens so tested.

Copper steel carrying small percentages of molybdenum is also used where a corrosion-resisting material is required.

Hayward and Johnston have shown that high-copper steel containing 0.86 per cent copper, 0.30 per cent carbon, and 0.012 per cent phosphorus has high values of yield point, tensile strength, and hardness, and good ductility. The behavior of this copper steel is similar to that of nickel structural steel; it has been used in long-span bridges.

248. Manganese Steel. Manganese steel usually contains from 11 to 14 per cent manganese and from 0.8 to about 1.5 per cent carbon.

When cast in the ingot, manganese steel is brittle and so hard that it is extremely difficult to machine. Reheating to about 1000° C. (1832° F.), followed by quenching in water, has the remarkable effect of rendering the material very much tougher and very much more ductile without materially altering its hardness. No treatment will materially soften manganese steel when cold, and it is therefore usually cast to as nearly its final form as possible and subsequently finished by grinding. Manganese steel is very fluid when molten, and sound castings are produced, although the shrinkage is excessive. The metal may be worked or forged with great difficulty through a short range of temperatures above a red heat. It is practically non-magnetic under all circumstances.

Structure and Constitution. The presence of manganese in the amount normally found in manganese steels has been shown to be responsible for the complete suppression of the allotropic changes which normally occur in the heating or cooling of carbon steels. Manganese steel has no critical points.

Tensile Properties. The following facts concerning the tensile properties of manganese steel appear to be established by a series of tests made by Hadfield.

The tensile strength of water-quenched steels containing in excess of 7 per cent manganese mounts rapidly with increase in manganese until a maximum of more than 140,000 pounds per square inch is reached with about 13 or 14 per cent manganese. With still higher manganese content the strength rapidly falls off again.

More important than the tensile strength of the quenched steels, however, is the ductility developed. With only 7 per cent manganese the elongation is only about 1.5 per cent in 8 inches, but it rapidly increases with increase in manganese until a maximum elongation exceeding 50 per cent is reached when the manganese content is about 13 or 14 per cent. Further increases in manganese rapidly decrease ductility. The ductility and the tensile strength remain practically directly proportional for all percentages of manganese.

A comparison of the elongation of the quenched steel and the forged steel containing about 13 or 14 per cent manganese reveals the fact that the elongation has been raised by quenching from about 1 or 2 per cent to more than 50 per cent. At the same time the strength has been increased about 100 per cent, and the hardness has not been materially impaired. Some of these bars were bent cold, after testing, nearly 180 degrees. In none was there any sign of necking down, but the contraction of area and distribution of elongation were nearly uniform over the entire length of the reduced section of the test bars.

The elastic limit is very low in proportion to the tensile strength. For the steels containing from 13 to 15 per cent manganese the stress at the elastic limit amounted to only 35 to 40 per cent of the tensile strength, being about 50,000 pounds per square inch for the steels whose tensile strength exceeded 140,000 pounds per square inch.

The outstanding properties of manganese steel are its extreme tough-hardness, and resistance to wear by abrasion, rather than its tensile properties.

Manufacture and Uses. Manganese steel is made by the open-hearth process whenever large masses are required. It may be made in the crucible, however. Manganese is added to the steel in the form of ferromanganese just before the completion of the process.

Large quantities of manganese steel are used as steel castings, particularly where great hardness and strength combined with great toughness are called for. It finds a special application in the construction of those parts of crushing and grinding machinery which are subjected to severe shock and abrasion. It is also used for curve rails, frogs, and crossings where hardness and freedom from brittleness constitute a great advantage, and to a limited extent for axles and treads of wheels of railway rolling stock. Its principal limitation in machine construction is the practical impossibility of machining it to final form by ordinary methods, on account of its excessive hardness.

249. Chromium Steel. Chromium steel, more commonly termed chrome steel, generally contains either from 0.50 to 2.0 or from 11.0 to 14.0 per cent chromium, with a variation in carbon content of 0.10 to 1.50 per cent. Its value is due principally to its property of combining intense hardness after quenching with very high strength and extremely high elastic limit. It is therefore especially well able to withstand abrasion, cutting, or shock. The value of the high-chromium steels is greatly enhanced by their resistance to corrosion.

Structure and Constitution. Thermal Critical Points. The characteristic structure of chrome steels containing less than about 5 or 6 per cent chromium does not differ materially from that of carbon steels similarly treated except for the presence of emulsified or finely granulated chromium carbide. With more than about 6 per cent chromium the structure of annealed steel "consists of chromiferous ferrite containing particles of double or triple (chromium) carbides, the carbide masses varying in size, some being very minute specks, and others of considerable dimensions."

Chrome steels possess distinct critical temperatures corresponding to those of ordinary carbon steels. The effect of the chromium, however, is to raise slightly the critical temperature in heating and to lower considerably the critical temperature on cooling. Maximum hardness and grain refinement are not attained by quenching from slightly above the critical temperature, 830°–843° C. (1525°–1550° F.), but by quenching from a much higher temperature, usually between 982° and 1038° C. (1800° and 1900° F.).

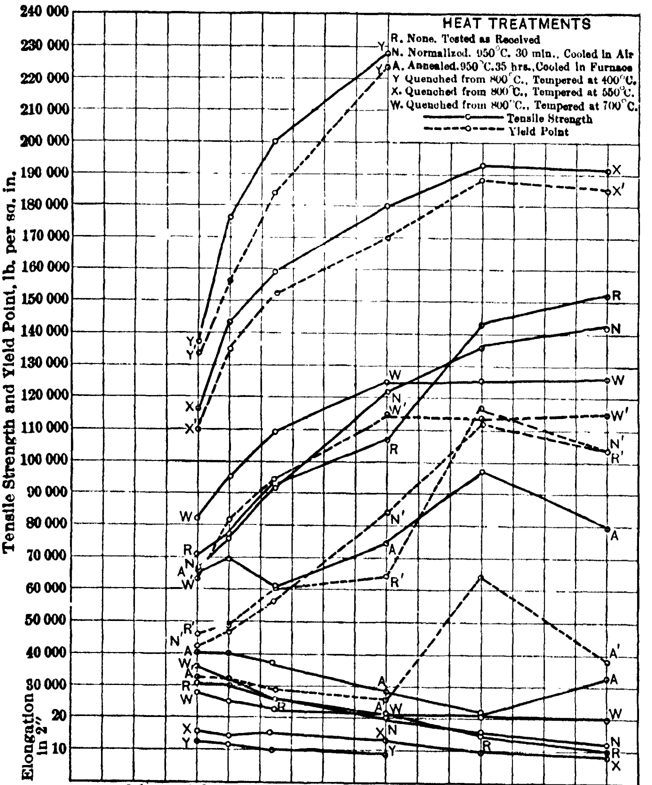


FIG. 81.—Relation of Tensile Properties of 2 Per Cent Chromium Steels to Carbon Content and Heat Treatment. (McWilliam and Barnes.)

Tensile Properties. The steels whose tensile properties are indicated by the curves of Fig. 81 represent fairly well the commercial chrome steels. The tests upon which these curves are based constitute a portion of the study of the physical properties of 2 per cent chrome steels made by McWilliam and Barnes. The relation between tensile properties, carbon content, and heat treatment of 2 per cent chrome steels is well shown by these tests.

The following general statements cover the most important facts as established by this series of tests.

The tensile properties of chrome steels, whether heat-treated in any manner or not, are dependent upon the carbon content to a very marked degree.

In general the tensile strength and yield point increase rapidly, and the ductility decreases as the carbon content increases. The maximum beneficial effect of carbon would usually seem to be attained when the carbon content does not greatly exceed 0.7 or 0.8 per cent. (An exception to this statement must be made for steels that have been neither hardened and tempered nor annealed.)

The yield point of 2 per cent chrome steels is remarkably close to the tensile strength if the steel has been quenched and tempered. With moderate tempering the yield point may exceed 95 per cent of the tensile strength.

The tensile properties of chrome steels which have not been heat-treated do not excel those of ordinary steel of similar carbon content in any way except that they are slightly more ductile.

The tensile strength is about doubled, the yield point about tripled, and the ductility reduced about one-half, by quenching from 800° C. (1472° F.), followed by tempering at 400° C. (752° F.). Tempering at higher heats reduces the strength and yield point and increases the ductility in proportion to the tempering heat employed.

Quenching followed by moderate tempering raises the tensile strength of 0.2 per cent carbon steel from 67,000 to 137,000 pounds per square inch, and the yield point from 42,000 to 134,000 pounds per square inch. When the carbon content is 0.5 per cent, this same treatment raises the tensile strength from 122,000 to 228,000 pounds per square inch, and the yield point from 84,000 to 224,000 pounds per square inch.

By prolonged annealing at high heats, the tensile strength is very much reduced, the yield point is lowered even more in proportion, while the ductility is very notably increased.

When it is recalled that the possession of this high strength and yield point is combined with a hardness almost equal to that of manganese steel, the commercial value of this class of steel may be appreciated. It is rather lacking in ductility, but this is often unimportant in view of its extremely high elastic limit.

Resistance to Corrosion. The low-chromium steels corrode less rapidly than the carbon steels, and the higher-chromium steels offer resistance to corrosion to such a marked extent that they have become known as stainless steels. Steels containing chromium in percentages greater than those usually found in the stainless steels are particularly useful because of their oxidization-resistant properties and high strength through the higher temperature ranges.

It should be stated that the stainless properties of the high-chromium steels can be fully developed only through proper hardening and surface polishing. The steels are susceptible of a very high polish, and the rustless properties increase with the smoothness of the surface.

Manufacture and Uses. Chrome steel is made in the crucible or in the open-hearth furnace. Chromium is added in the form of ferrochrome, which oxidizes easily, so that the loss will be very heavy in the open hearth unless it is added just before the end of the process.

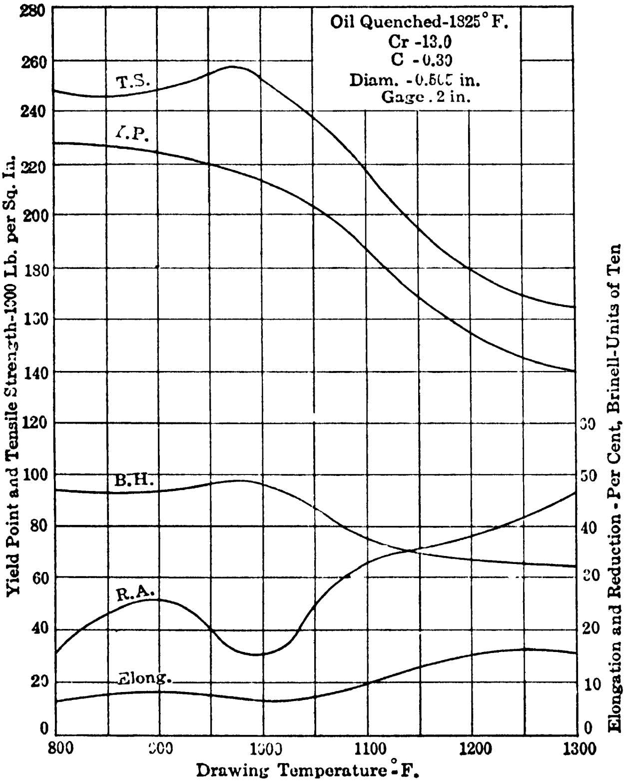


FIG. 82.—Stainless Steel. (Oil Quenched.)

Low-chrome steel is used where an extremely hard surface and shock resistance are desired. All high-grade balls, rollers, races, etc., for bearings are made of chrome steel. It is used in the manufacture of armor-piercing projectiles and armor plate, also for a limited class of tools and dies, for gears and other parts of automobiles and machines generally, for the wearing parts of rock-crushing machinery, and for safes and vaults. For safes and vaults, chrome steel is welded with alternate layers of wrought iron into a composite 3- or 5-ply plate. The chrome steel resists cutting by drills while the wrought iron introduces an element of toughness so that it is better able to withstand concussion.

The high-chromium steels are of great value where their stainless and rustless properties are desirable, or where a steel is required to withstand stress and corrosion at high temperatures, as in oil-cracking apparatus.

Stainless steel containing about 13 per cent chromium is air-hardened; therefore it cannot be normalized in the usual manner. It is commonly quenched in oil or water from a temperature of 925°–1090° C. (1700°–2000° F.) and then tempered between 315° and 735° C. (600° and 1350° F.). The lower tempering temperatures give a tensile strength of about 200,000 pounds per square inch with a hardness of at least 450 Brinell; the higher tempering decreases the tensile strength to about 130,000 pounds per square inch with a corresponding decrease in hardness and a marked increase in ductility. (See Fig. 82.)

Stainless iron is now being produced in large quantities. It differs from stainless steel simply in its low carbon content, usually having from 0.05 to 0.07 per cent instead of the 0.30 per cent of stainless steel. It is somewhat less resistant to corrosion than the steels but, because of its greater ductility, is more useful in the manufacture of plates and other rolled shapes.

250. Tungsten Steel. Tungsten has long been recognized as a valuable alloy element for special steels. It is, however, most commonly used in conjunction with chromium or manganese in a quarternary alloy, instead of with carbon alone as a ternary alloy. The ternary alloys of iron, tungsten, and carbon possess a certain amount of commercial importance, however.

Tungsten steel usually contains from 3 to 10 per cent of tungsten and from 0.2 to 1.0 or even 1.5 per cent carbon. The tensile properties of tungsten steel resemble those of high-carbon steel, the strength and especially the elastic limit being high, but the ductility low. After moderately rapid cooling from high temperatures, however, the tungsten steels exhibit remarkable hardness which is still retained upon heating to temperatures considerably above the ordinary tempering heats of carbon steels. It is this property of tungsten which makes it a valuable alloy, in conjunction with chromium or manganese, for the production of "high-speed" tool steels.

The tungsten steel which contains about 4 or 5 per cent of tungsten and 0.5 to 0.7 per cent carbon possesses remarkable magnetic reluctance.

It is a valuable material therefore for permanent magnets, since, when once magnetized, it retains magnetism much longer than ordinary iron or steels.

Tensile Properties. The tensile properties of two series of steels containing from 0.4 to 27.05 per cent tungsten, together with about 0.2 per cent and about 0.8 per cent carbon, respectively, are shown in the diagrams of Fig. 83. It will be noted that for both series of steel the tensile strength and elastic limit increase with increase in tungsten until a maximum strength is reached, with 10 per cent and 12 per cent tungsten, respectively, in the high- and low-carbon steels. The ductility is also reduced with increase in tungsten. (These steels have been heated 3 hours at 850° C. [1562° F.], prior to testing.)

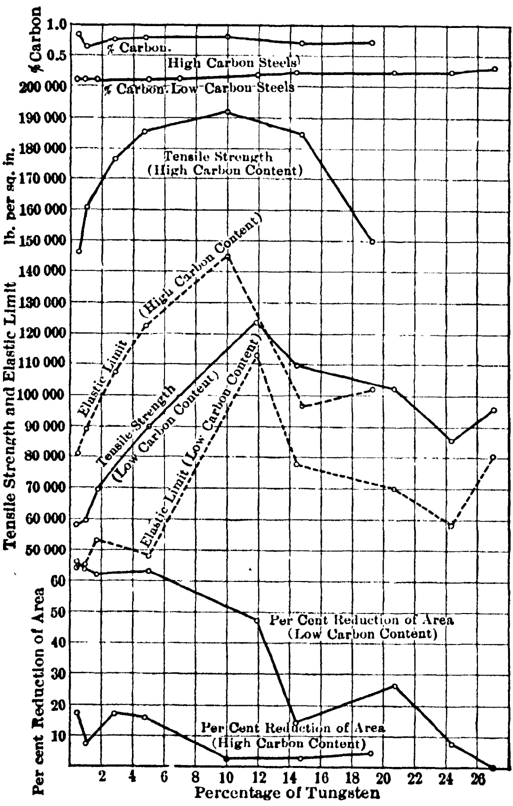


FIG. 83.—Tensile Properties of Tungsten Steels. (Portevin.)

The marked difference in the properties of a high- and a low-carbon tungsten steel is shown by a comparison of the curves of Fig. 83.

Manufacture and Uses. Tungsten steel is made almost exclusively by the crucible process, the tungsten being added in the form of ferro-tungsten, as wolframite, or, less commonly, as metallic tungsten. Uses of tungsten steels are given in Table XXVII.

251. Molybdenum Steel. The action of molybdenum in steels is generally considered to be similar to that of tungsten so far as the influence of the alloy upon critical temperatures, hardening power, physical properties, etc., are concerned, but the effect of molybdenum differs in mag-

TABLE XXVII

USES OF COMMERCIAL STEELS CONTAINING TUNGSTEN

Type Composition, per cent				Used for
Carbon	Tungsten	Chromium	Vanadium	
0.50 to 0.65	0.50 to 2.00	....	....	Chisels
0.65 to 0.80	4.50 to 7.00	....	....	Permanent magnets
1.00 to 1.20	1.25 to 2.50	....	....	Keen-edged tools, taps, chasers, etc.
1.00 to 1.20	1.00 to 2.00	0.50 to 1.00	....	
1.10 to 1.30	4.50 to 6.00	1.00 to 1.50	....	For finishing tools, for gun rifling, etc.
0.30 to 0.45	8.00 to 11.00	2.50 to 3.50	0.30 to 0.60	For hot-working dies, shears, etc.
0.30 to 0.55	1.50 to 2.50	1.25 to 2.00	0.15 to 0.40	For hot-working dies, chisels, etc.
0.50 to 0.70	1.50 to 2.00	0.50 to 1.00	....	For valves for gasoline motors
0.50 to 0.70	12.00 to 15.00	3.00 to 4.00	....	
0.60 to 0.70	1.00 to 3.00	....	....	For making gun and Howitzer linings
0.50 to 0.80	12.00 to 20.00	2.50 to 5.00	0.50 to 2.25	The very broad analysis of high-speed steel, with innumerable uses
	(With or without other elements)			

nitude from that of tungsten, 1 per cent of molybdenum being apparently equivalent to 2 or 3 per cent of tungsten.

Most molybdenum steels are really quaternary alloys, since chromium or manganese is usually present in notable amounts. The best molybdenum ternary alloy steels contain from 1 to 2 or 3 per cent molybdenum and not more than 0.2 per cent carbon. The general physical characteristics of molybdenum steels are about the same as those of tungsten steel.

In small percentages molybdenum improves the machinability of steels. Molybdenum steels retain their mechanical properties at elevated temperatures better than other steels of low alloy content. Welding of molybdenum steels is not more difficult than of carbon steels.

Tensile Properties. The tensile properties of a series of molybdenum steels containing from 1.0 to 8.0 per cent molybdenum and 0.2 to 1.2 per cent carbon are shown by the curves of Fig. 84. These tests constitute a portion of Swinden's study of molybdenum steels.

The diagram is self-explanatory, and it will not be necessary to discuss it beyond the point of simply calling attention to the fact that with a given molybdenum content the strength and elastic limit are increased and the ductility decreased rapidly as the carbon content is raised. Quenching from a temperature of 800° C. (1472° F.) to 900° C. (1652° F.) is very beneficial to tensile properties with the exception of ductility.

Manufacture and Uses. Molybdenum steels are made in the crucible in the same manner as tungsten steels, and have practically the same uses.

252. Vanadium Steel. Vanadium, with the single exception of carbon, is the most powerful element for alloying with iron yet discovered. Only 0.1 to 0.15 per cent of vanadium raises the tensile strength and elastic limit of low- or medium-carbon steel 50 per cent or more without any sacrifice of ductility. With high carbon content (about 0.8 per cent carbon), and about 0.2 per cent vanadium, the tensile strength is about equal to that of an ordinary steel of corresponding carbon content, but the elastic limit is very much higher and the steel is much more ductile than a similar carbon steel.

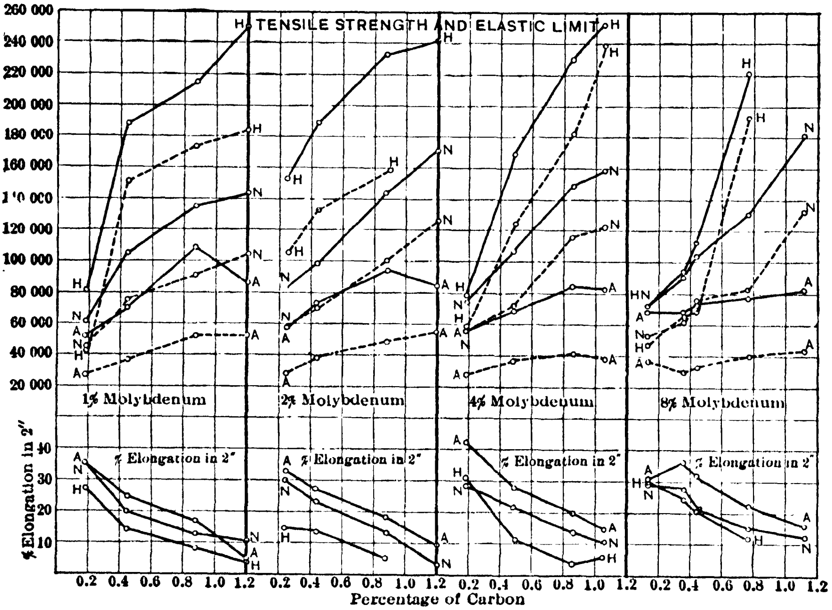


FIG. 84.—Tensile Properties of Molybdenum Steels. (Swinden.)

Tensile Strength——————o——————
Elastic Limit ....o..........
N, Normalized, 15 min. at 900° C. (1652° F.), Air Cooled.
A, Annealed, 5 hr., at 950° C. (1742° F.), Cooled in Furnace.
H, Hardened and Tempered, Quenched at 950° C. (1742° F.) to 800° C. (1472° F.) in Oil.

Little more than 0.2 per cent vanadium seems to be advantageous in any steel, and amounts exceeding about 0.3 per cent are very detrimental to strength.

Vanadium steels may be forged or rolled with only minor special precautions; they respond readily to heat treatments; are enormously strong when hardened by quenching and moderately tempered; and are very tough, and stand impact, vibration, or reversal of stress very well.

Vanadium has an important quieting influence upon molten steel when cast in the ingot, and therefore promotes soundness by preventing the occlusion of gases.

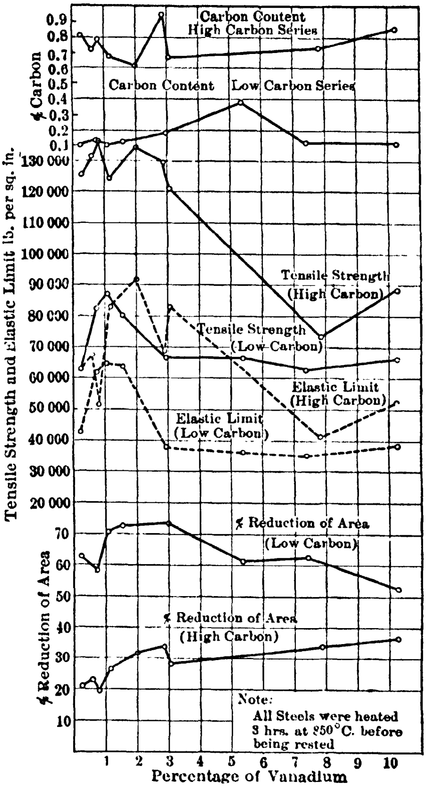


Fig. 85.—Tensile Properties of Various Vanadium Steels. (Portevin.)

The use of vanadium in steels designed for a great variety of purposes is becoming more common every year, and, in addition to the ternary alloys of vanadium, carbon, and iron, vanadium is used in a variety of quaternary alloy steels in which chromium, nickel, etc., are also present.

Structure and Constitution. The structure and constitution of vanadium steels, either normal or heat-treated, do not differ from those of corresponding carbon steels. The vanadium appears to exist for the most part as a carbide, but a small amount is usually present in the free ferrite. The thermal critical points seem not to be markedly affected by the small amount of vanadium added.

Tensile Properties. The tensile properties of two series of steels containing about 0.2 per cent and about 0.8 per cent carbon, respectively, are shown in Fig. 85.

The beneficial effect of 0.1 to 0.3 per cent vanadium upon tensile strength and, more particularly, the elastic limit, is plainly shown by these tests. The remarkable ductility of these steels, as indicated by the percentage of reduction of area, is also worthy of special note.

Vanadium steels are very responsive to heat treatments, the effect of the hardening treatment followed by moderate tempering being especially remarkable because of the extent to which the yield point and, less notably, the tensile strength is raised.

Manufacture. Vanadium steels were originally made in the crucible, but are now commonly made in large masses in the open hearth. The vanadium is added in the form of ferrovanadium, introduced after the recarburizer has been added when the conditions of the process are reducing rather than oxidizing, in order to avoid loss by oxidation.

Vanadium steel is used to a considerable extent for castings and forgings for machines, automobiles, and railway rolling stock, also for axles, springs, shafting, and gears. A structural grade of vanadium steel has recently been introduced, the material being rolled to the ordinary structural shapes and used in the construction of long-span bridges and other structures subjected to severe conditions of service.

Vanadium-steel castings are considerably tougher, stronger, and more wear-resistant than carbon-steel castings. They approach the properties of manganese-steel castings in these respects.

QUATERNARY STEELS

253. Chrome-nickel Steel. Chrome-nickel steels are of the first order of importance. They usually contain from 0.30 to 2.0 per cent chromium, from 1.0 to 4.0 per cent nickel, and from 0.10 to 0.60 per cent carbon. These steels, when properly heat-treated, have a very high tensile strength and elastic limit, together with great toughness and considerable ductility. They are markedly resistant to repeated stress and impact.

Structure and Thermal Critical Points. The structures of chrome-nickel steels are essentially similar to those of steel containing slightly greater percentages of nickel and no chromium, with the addition of minutely divided carbides of a complex nature. The combined effect of the two alloying elements is slightly to lower the critical temperature on heating and to depress the critical temperature on cooling very greatly, enough under certain conditions to produce an air-hardening steel.

Tensile Properties. The tensile properties of this group of steels are excellent, as will be noted from Figs. 86, 87, and 88. The analysis of the steel in Fig. 86 is typical of a low-carbon case-hardening steel, where core-toughness is of more importance than high tensile strength. The steel in Fig. 87 is adaptable for oil-hardened parts, either machined or forged, which require high physical properties. The properties of an air-hardening chrome-nickel steel are shown by Fig. 88. This steel is possessed of remarkably high strength, toughness, and resistance to dynamic stresses.

Castings of chrome-nickel steel, with its characteristic high strength and toughness, are sometimes made. Heat-treated steel castings containing 0.30 carbon, 2.50 nickel, and 0.50 chromium have developed a tensile strength of 110,000 pounds per square inch, and an elastic limit of 80,000 pounds per square inch, with percentage reduction of area and elongation of 30 and 20 respectively.

One of the recently developed high-chromium-nickel steels contains 16.5 to 19.5 per cent chromium, 7.0 to 10.0 per cent nickel, and less than 0.15 per cent carbon. It is sold under various trade names, as "Enduro Nirosta," K.A. 2, 18–8, "Alleghany metal," etc. It is austenitic in all temperature ranges and, therefore, cannot be heat-treated in the same manner as ordinary steels but must be altered in physical properties by cold-working followed by annealing. In this manner its tensile strength may be varied from 85,000 to 150,000 pounds per square inch. Its ductility, very curiously, decreases with decreasing tensile strength. This steel is remarkably resistant to atmospheric corrosion and to many types of chemical attack. It may be forged, welded, brazed, and soldered and is available in cast form and in any of the usual shapes and wire sizes.

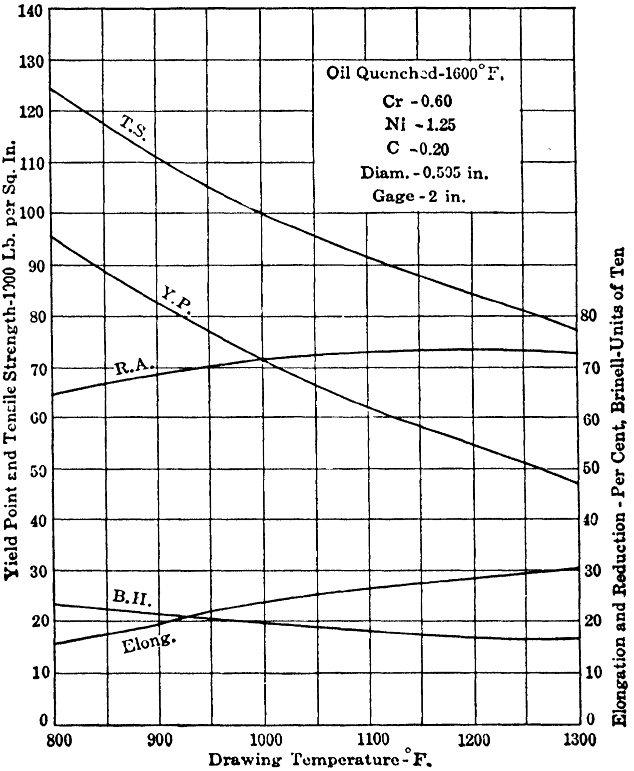


FIG. 86.—Chrome-nickel Steel (Oil Quenched 1600° F.).

Manufacture and Uses. Chrome-nickel steels are made by the open-hearth, crucible, and electric-furnace processes. Certain Cuban ores containing about 1.5 per cent nickel and 3 per cent chromium are used in the manufacture of a natural chrome-nickel steel known as "Mayari" steel.

Chrome-nickel steels are used for case-hardened gears and machine parts, for forged axles, crankshafts, propeller shafts, and connecting rods, for armor plates and projectiles; and Mayari steel, for rails and structural members.

High-chromium-nickel steel of the 18–8 type is utilized in light-weight high-strength structural applications. Light weight is obtained by utilizing its high tensile strength and by simplification of structural parts and connections by employing welding, particularly spot welding (Art. 122), instead of riveting. Resistance to corrosion of this steel makes it durable and attractive as a surfacing material. Thin sheets can be used without fear of corrosion subsequently reducing effective sections. An important application is in the construction of streamline, light-weight railroad cars. The exterior surfaces and the major portion of the car structures are fabricated from this high-chromium-nickel steel. This steel has also been employed to a limited extent in the construction of airplane structures in competition with light-weight alloy materials.

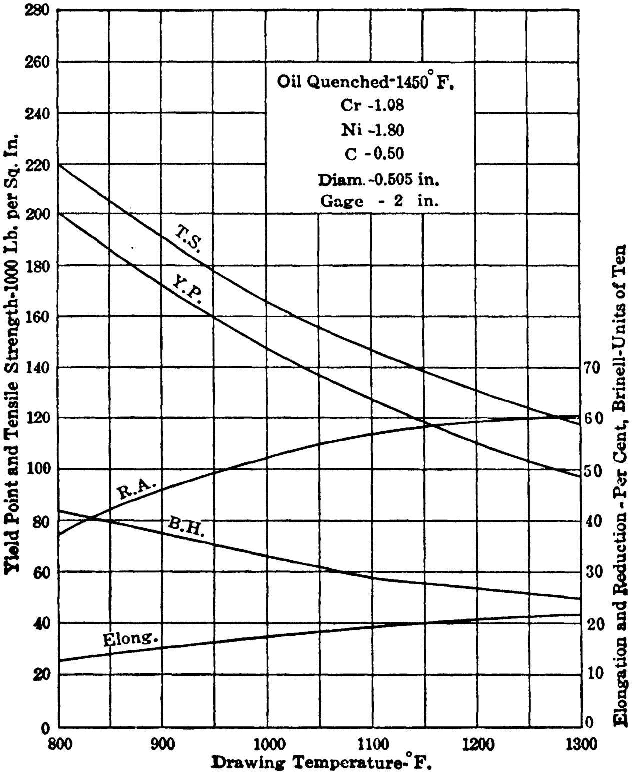


Fig. 87.—Chrome-nickel Steel (Oil Quenched 1450° F.).

Steel of 18–8 type should not be used for temperature conditions above 704° C. (1300° F.) under pressure because of grain growth, brittleness, and tendency to fail suddenly. The alloy steel of composition 25 per cent chromium, 20 per cent nickel, and 2 per cent silicon is suitable for high-temperature conditions up to about 982° C. (1800° F.).

High-chromium-nickel alloy steels are sometimes welded onto mild carbon steel in order to secure the economy of having a thin layer of alloy steel on a relatively heavy backing or core of the cheaper mild steel and to secure the advantage of corrosion resistance of the alloy steel.

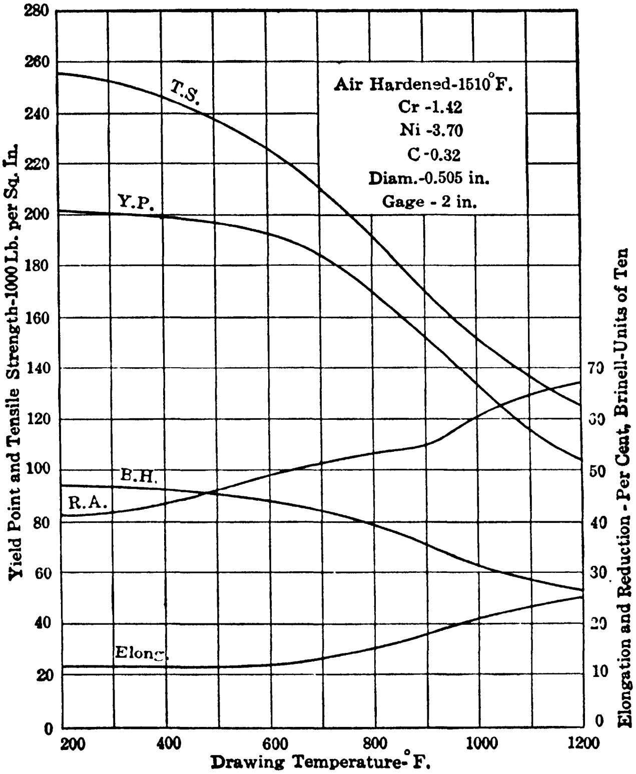


Fig. 88.—Chrome-nickel Steel (Air Hardened).

254. Chrome-vanadium and Chrome-molybdenum Steels. The quaternary steels of the chrome-vanadium and chrome-molybdenum varieties closely resemble the chrome-nickel steels. The usual composition limits for the chrome-vanadium steels are: chromium 0.50 to 1.50, vanadium 0.15 to 0.30, and carbon 0.15 to 1.10 per cent. The chrome-molybdenum steels generally contain less than 1.0 per cent molybdenum, with 0.50 to 1.50 per cent chromium and 0.15 to 1.0 per cent carbon.

These steels possess great strength and toughness when properly heat-treated; and recent investigations indicate that they can be successfully forged and heat-treated within wider temperature ranges than chrome-nickel steel, although their present use is not so extensive.

Tensile Properties. The tensile properties of heat-treated chrome-vanadium and chrome-molybdenum steels are shown in Figs. 89 and 90.

Manufacture and Uses. Chrome-vanadium steel is manufactured by the open-hearth, crucible, and electric-furnace processes; the manufacture of chrome-molybdenum steel is largely by the open-hearth process.

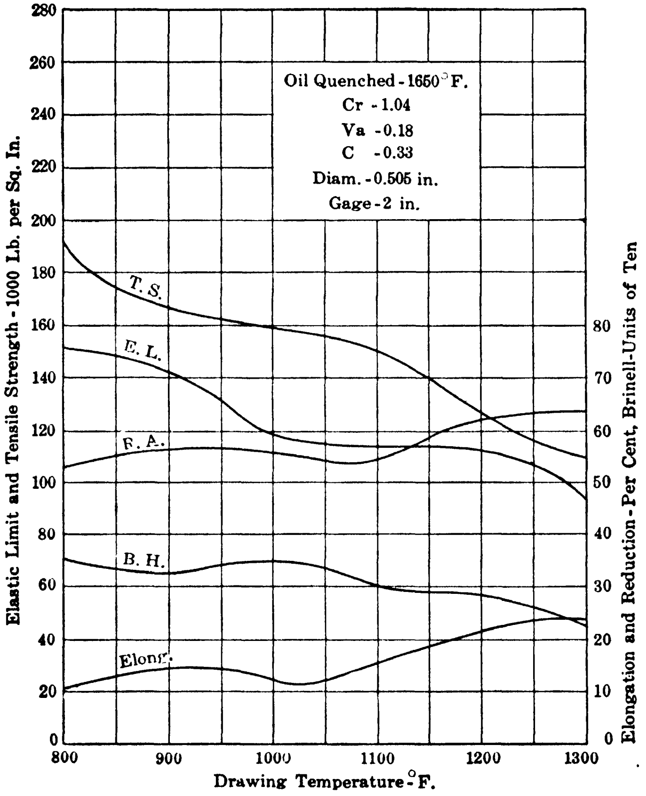


FIG. 89.—Chrome-vanadium Steel (Oil Quenched 1650° F.).

These steels are used for heat-treated forged or machined parts which require a high strength and elastic limit, coupled with toughness, ductility, and shock resistance. Chrome-molybdenum steel is of value in the aircraft industry on account of its freedom from scale and good resistance to abrasive wear.

255. Chrome-silicon and Manganese-silicon Steels. The chrome-silicon steels generally contain from 5.0 to 18.0 per cent chromium, 1.0 to 4.0 per cent silicon, and 0.10 to 1.10 carbon. These steels offer good resistance to corrosion. A steel containing 16.5 to 18.5 chromium, 0.75 to 1.50 silicon, and carbon under 0.15 per cent possesses the stainless properties of the lower-chromium stainless steels and is much easier to machine. Another chrome-silicon steel containing 5.0 to 7.0 chromium, 2.0 to 4.0 silicon, and 0.40 to 0.50 per cent carbon retains its hardness at a red heat and oxidizes very slowly at this temperature. This steel is used extensively for airplane and automobile engine valves.

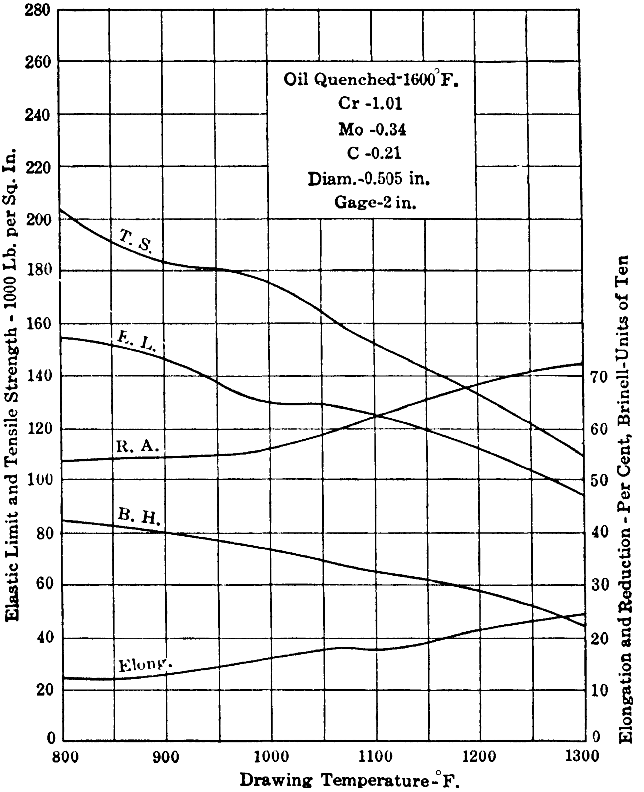


FIG. 90.—Chrome-molybdenum Steel (Oil Quenched 1600° F.).

The manganese-silicon steels are not unlike the straight silicon steels but are in no way similar to the ternary manganese steels. They generally analyze as follows: manganese 0.60 to 1.0, silicon 1.80 to 2.20, and carbon 0.40 to 0.60 per cent. This steel is used extensively for springs and to a limited extent for gears, etc. It has a rather narrow heat-treating range and can be treated successfully only by close temperature control.

256. Aluminum Steels. A recently developed group of steels contains about 1.25 per cent of aluminum, 1.5 to 1.6 per cent of chromium, and about 0.2 per cent of molybdenum. These steels have excellent mechanical properties and, in the annealed condition, show a tensile strength of about 90,000 pounds per square inch and an elongation of 30 per cent in 2 inches. They may be heat-treated to show a tensile strength of more than 200,000 pounds per square inch with an elongation of about 11 per cent.

The peculiar characteristic of these steels, known as "Nitralloy," is their ability to absorb nitrogen on the surface, producing a case which is much harder than that produced by the ordinary methods of case-hardening with carbon. The operation is known as "nitriding." A carbon steel can be nitrided, but the operation is slow and relatively little hardness is obtained compared to that of aluminum alloy steel. The alloy steel should be in the sorbitic condition to get best results.

257. Nitriding. Before nitriding, the steel should be annealed thoroughly, then hardened by quenching from about 926° C. (1700° F.) in oil, followed by tempering at about 593° C. (1100° F.). After heat treatment the steel should be machined; sections of the metal deficient in carbon should be removed.

Heating is carried on in a current of ammonia gas at 480–593° C. (900–1100° F.) for a period of time depending upon the depth of case required. At a temperature of about 480° C. (900° F.) small penetration but maximum hardness are obtained; at 593° C. (1100° F.) increased penetration but low hardness result. A two-step method is sometimes employed in which a temperature of 480° C. (900° F.) is first maintained to get maximum hardness; then the temperature is raised to 593° C. (1100° F.) to get deeper penetration. Strangely enough the hardness gained at the lower temperature is retained and the hardness of the outside of the case does not affect penetration depth when the temperature is raised to 593° C. (1100° F.). The longer the process, the deeper the case. The length of time depends on the job and may require from 10 to 90 hours. A special reaction chamber is required, a steel chamber being satisfactory. Either a gas or an electric furnace can be used. The treated steel is cooled in the furnace. No follow-up heat treatment is necessary.

Nitriding will produce a steel with a surface hardness of 900 to 1100 Brinell and with a marked resistance to corrosion. The change in dimensions during nitriding is so slight that for most purposes it is negligible, and, as the operation is carried out at a comparatively low temperature, the danger of distortion, which always occurs in case-hardening, is practically eliminated. The hardness of 1100 as compared with 650 as found in ordinary carbon hardening makes these steels remarkably resistant to wear and abrasion. Nitrided nitralloy is being used for bushings, cams, gauges, cylinders, spinner rings, crankshafts, and similar parts.

QUESTIONS

1. What is an alloy steel?

2. Describe the Society of Automotive Engineers numbering system for steels.

3. Identify the steels corresponding to the following S.A.E. numbers: 1030, 3215, 5140, 6150, 9255, 71660.

4. Sketch the Guillet diagram for nickel alloy steel.

5. Does nickel steel sometimes have austenitic structure at ordinary temperature? Explain why.

6. What are the special properties of low-nickel alloy steels?

7. Why is a low-nickel alloy steel valuable as a structural steel?

8. What are the composition and outstanding characteristic of Invar steel?

9. State the physical properties of silicon alloy steel used for structural purposes.

10. What is "Navy" steel?

11. Why is silicon alloy steel used for electrical machinery?

12. Compare the corrosion resistance of copper-bearing and non-copper-bearing ferrous metals.

13. What are some of the outstanding properties and uses of manganese steel?

14. What percentages of chromium and carbon are usually contained in chromium alloy steel?

15. What are the physical properties of chromium steel?

16. What conditions in the service required of a given mechanical part would determine your choice between a simple nickel or simple chromium alloy steel?

17. What is "stainless" steel?

18. What are some of the uses of commercial steels containing tungsten?

19. Compare the effect of molybdenum with that of tungsten as an alloying element.

20. Describe the tensile properties of vanadium alloy steels.

21. Describe the tensile properties of low-chrome-nickel alloy steel.

22. What is meant by the term "18-8"?

23. Discuss the utilization of high-chromium-nickel alloy steels. How are they welded?

24. Describe in detail the process of nitriding.

25. State the type of steel or other ferrous metal that you would select as being the best suited for the following uses: (*a*) frog on a railway track, (*b*) important structural members of a long-span bridge, (*c*) ball bearings, (*d*) plates for exterior surfaces of a prominent building, (*e*) parts to withstand wear in a gyratory rock crusher, (*f*) armor plate for a battleship, (*g*) an automobile crankshaft, (*h*) a rear axle for a truck, (*j*) vats for holding corrosive liquids, (*k*) tank to withstand temperature of 900° C. under pressure, (*l*) pipe for fire main on ship for pumping salt water, (*m*) pole pieces of an electric motor, and (*n*) stainless-steel cutlery. State your reasons for each selection.

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CHAPTER XII

SERVICE REQUIREMENTS OF METALS

By Lloyd F. Rader

258. General. Requirements of metals in various types of service and under different conditions of exposure will be considered in this chapter. The resistance of metals to failure due to slip, progressive fracture under repeated stresses (fatigue), creep, impact, wear, and corrosion are described.

SLIP

259. Slip. Slip is the phenomenon of movement along gliding planes of crystals due to the application of stress above the elastic limit. Slip is an inelastic action that does not continue indefinitely under sustained stress but reaches a state of equilibrium after a short time. The occurrence and appearance of slip lines are described in Art. 29, and the slip-interference theory in Art. 100.

FRACTURE OF METALS UNDER REPEATED STRESSES

260. Behavior of Metals under Repeated Stresses. All metals may ultimately fail through repetition of stresses below the elastic limit. Such failures have often been observed in the case of axles, machine parts, shafts, etc., and the phenomenon has frequently been demonstrated in a scientific manner since the pioneer work reported by Wöhler in 1870. If the repeated stress approaches anywhere near the ultimate strength, failure may, in steels, be induced by very few repetitions, but with a maximum stress not far from one-half the ultimate strength, rupture, if ever attained, will usually be produced only by millions of repetitions.

This phenomenon was once ascribed to a general deterioration of the cohesion between crystalline constituents of the metal when subjected to many repetitions or reversals of comparatively low stresses. Owing probably to this idea of deterioration, the phenomenon came long ago to be known as the *fatigue* of metals, and the use of the term has persisted in spite of the fact that it is now known to be a process of gradual or *progressive fracture* of the crystals themselves.

Examination under the microscope of the behavior of the crystalline constituents of metals under repeated stress has shown that failure of crystals is caused by a succession of shear slips on parallel planes of least strength. The failure of the piece as a whole is due to the successive failure of individual crystals and the development of cracks. Failure very seldom occurs at crystalline boundaries.

Slip in crystals is likely to occur at points where high localized stresses are set up. These stresses are dependent chiefly upon the distribution of stress between crystals, which in turn is dependent upon the homogeneity of the structure. Thus flaws and cracks in the internal structure, sudden changes in cross-section, sharp corners, especially reëntrant angles, irregularities in surface finish, poor fitting of pins, rivets and bolts at connections, etc., may cause high localized stresses. The preëxistence of internal stresses, originating during cooling, heat treatment, or mechanical working, may cause concentrations of stress under service conditions. In general, these high localized stresses tend to increase as the average computed stress across a section is increased. Localized stresses do not ordinarily affect the static structural strength but tend to produce slip in crystals when the metal is subjected to repeated stress.

261. Character of Fracture. Test specimens of cylindrical shape rotated under reversed bending have fatigue cracks formed around the circumference. As the application of stress is continued, these cracks tend to increase in number and to extend inward until only a central core of uncracked metal is left. When the cross-section of this core becomes too small to withstand the load upon it, the core suddenly fractures at right angles to the direction of stress in a manner similar to the rupture of a brittle metal. The surface of the fracture of the core is rough and "crystalline" in texture and similar to that obtained by nicking the specimen and breaking by a sudden blow. The walls of the cracks are worn smooth by the alternate opening and closing of the cracks under reversed bending, thus producing a smooth surface on the exterior portion of the fractured cross-section.

262. Endurance Limit. The stress below which a material can withstand an indefinitely large number of repetitions of stress is defined as the *endurance limit* of that material. The endurance limit is determined by testing specimens in special testing machines for a number of cycles of stress of different magnitudes. The values are plotted with stress S as ordinates against cycles for rupture N as abscissas. A typical curve plotted to logarithmic scale is shown in Fig. 91. Such a curve is commonly called an S-N diagram. The unit stress for which the curve becomes horizontal is designated as the endurance limit. Most metals have a fairly definite endurance limit, but some metals as, for example, duralumin have curves which do not become horizontal.

263. Fatigue-testing Methods. Metals are usually tested under alternating or *reversed stress* where stress changes from one direction to the opposite one. Stresses may be applied wholly in one direction, however, either in tension or in compression. These stresses are called *swelling* stresses. *Repeated stress* is a general term covering both cases.

Both notched and unnotched specimens are used in testing. The notched specimens have a lower endurance limit.

A large amount of data has been obtained on fatigue properties of metals by using the R. R. Moore rotating beam machine with the bending moment applied through holders at operating speeds of 1725 and 3450 cycles per minute. Oberg and Johnson * employed a similar type of machine with ball-bearing housings supporting nitrided-steel spindles for holding the specimen which can be rotated at a speed of 10,600 cycles per minute. Tests at this speed gave endurance limits for a number of metals comparable with those obtained at lower speed. The rate of speed may affect the shape of the *S-N* diagram at stresses above the endurance limit. A speed of 10,000 cycles per minute makes it possible to obtain endurance limits of satisfactory precision for most metals in a moderate length of time.

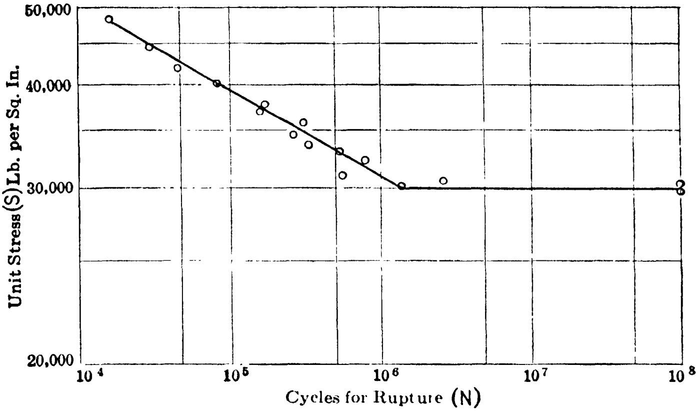

Fig. 91.—Determination of Endurance Limit (Logarithmic Scale).

Special testing machines are used for fatigue testing at elevated and low temperatures.

During testing it is sometimes desired to detect the presence of fatigue cracks. One method consists of placing oil in the cracks by applying oil to the metal surface and then rubbing the surface free from oil. A coating of thin white paste is applied. The piece is set up on supports and subjected to a sudden blow to set up bending stresses which will close the

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* T. T. Oberg and J. B. Johnson: Fatigue Properties of Metals Used in Aircraft Construction at 3450 and 10,600 Cycles, *Proc. Am. Soc. Test. Mats.*, v. 37, Part II, 1937.

cracks, squeeze out the oil, and discolor the white coating. Another method is to magnetize the steel and sprinkle fine iron dust over it. A thin line of dust is formed by the magnetic poles at a crack. Some cracks can be observed by visual inspection or by means of a magnifying glass. These methods for detecting cracks can be applied in the examination of machine parts in service.

264. Machine Parts Subjected to Repeated Stress. Endurance limits are determined for metals that are to be used in the manufacture of machine parts subjected to rotation, bending, vibration, etc. Typical examples are axles, shafts, piston rods, connecting rods, well-drilling rods, steam turbine blades, and springs. Structural members in airplanes are subjected to repeated stress due to vibration.

265. Effects of Overstressing and Understressing in Fatigue. The effects of repeated stress above and below the endurance limit have been reported by Professor J. B. Kommers.* These effects are of importance because materials in service are frequently subjected to overstress, which is stress above the endurance limit, and are commonly subjected to understress, which is stress below the endurance limit.

Overstressing for a number of cycles may initiate cracking that will weaken the metal. The procedure of testing the metal for a number of cycles at an overstress and then reducing the load on the specimen to determine the value of the new endurance limit quite commonly reduces the endurance limit below that of the virgin metal. In general, the amount of damage due to overstress tends to increase with increase in the percentage of overstress and the cycle ratio. Cycle ratio is defined as the ratio of the number of cycles applied at a given overstress to the number of cycles at which the material would fail at that stress.

Periods of progressively increasing cyclic understress, on the other hand, may greatly increase the new endurance limit. This may be due to cold-working of the metal during the understressing period. Furthermore, progressively increasing cyclic understress, applied to a specimen after overstress, not only may repair the damage which has been done, but sometimes may augment the original endurance limit by a substantial percentage. Thus the endurance limit of a material is not a fixed quantity but may be changed by various conditions of stress.

266. Endurance Ratios. The ratios of endurance limit to tensile strength, torsional strength, etc., are known as *endurance ratios*. Tests have led to the establishment of endurance ratios for many of the ferrous metals after conditioning by various workings and heat treatments, and for most of the commercially important non-ferrous metals and alloys.

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* J. B. Kommers: The Effect of Overstressing and Understressing in Fatigue, *Proc. Am. Soc. Test. Mats.*, v. 38, Part II, 1938, pp. 249-268.

The endurance ratios for the worked ferrous metals vary considerably, but a fair value seems to be 0.5 of the ultimate tensile strength. For cast steel and cast iron this endurance ratio is about 0.4. For the non-ferrous metals this value varies between wide limits but is, as an average, lower.

267. Effects of Heat Treatment and Cold-working. The endurance limit of steel is increased by proper heat treatment. Steel of sorbitic structure has particularly good fatigue resistance. Annealing generally decreases the endurance of steel. Cracks formed by repeated stresses cannot be healed by annealing. The endurance limit of metals is increased by cold-working.

268. Effect of Carbon Content of Steels. As the percentage of carbon is increased, the proportion of relatively coarse crystals of ferrite decreases, and the endurance of steels under repetitions of stress normally tends to increase until the carbon content approaches the eutectoid ratio. The relation of carbon content to the endurance of steels is very often masked, however, by the effect of other factors. Thus any heat treatment which tends to increase the size of crystals formed is very detrimental to endurance, and the presence of comparatively large amounts of phosphorus, manganese, etc., or the existence of internal stresses caused by the conditions of cooling, heat treatment, or mechanical working, may be factors whose influence outweighs that of carbon content.

269. Endurance Limits at Elevated and Low Temperatures. For temperatures up to about 300° C. (572° F.) a number of metals show an increase in endurance limit as compared with that developed at normal temperature. The fatigue strength of practically all metals drops off at temperatures above 500° C. (932° F.). Some alloy steels, as, for example, 12 per cent chromium steel, some tempered carbon steels, and some non-ferrous alloys such as aluminum alloys show a decrease in endurance limit for all elevated temperatures.

The endurance limit of certain carbon steels at low temperatures has been found by Professor O. H. Henry of the Polytechnic Institute of Brooklyn to be greater than at normal temperature.

270. Fatigue Strength of Welds. Henry and Amatulli found an endurance limit of 35,000 pounds per square inch for a joint of 0.18 per cent carbon steel welded with steel of an original endurance limit of 35,000 pounds per square inch. The welding was carefully executed by the electric-arc method using a coated electrode rod which gave off a non-oxidizing gas that protected the weld metal from oxidation. Additional tests at 300° C. (572° F.) on the same weld gave an increased endurance limit of 41,000 pounds per square inch, but fatigue resistance was reduced at 500° C. (932° F.). Somewhat lower fatigue strengths may be expected for field welds and particularly for welds made with plain electrodes.

CREEP

271. Creep. Creep is the slow flow which takes place in solid materials under sustained stress at elevated temperature. This phenomenon occurs in materials such as lead and zinc at normal temperatures under relatively low stresses, but most metals have to be at a high temperature before appreciable flow occurs. Creep may continue indefinitely under sustained stress tending to distort the material, and may cause failure by rupture. Creep affects the entire body of the material under stress instead of producing a localized rupture which occurs under repeated loading.

Four variables are involved in creep testing: stress, temperature, deformation, and time. Usually creep tests are conducted on tensile specimens under constant stress and temperature conditions so that the relations between deformation and time can be determined.

272. Creep of Steel. The influence of time on the creep characteristics of carbon steel at 538° C. (1000° F.) as determined by the Department of Engineering Research, University of Michigan, for different stresses, is shown in Fig. 92.* The slope of the time-elongation curve is a measure of the rate of flow. The rates of creep may be divided into three stages; the creep rate is rapidly decreasing in the first stage, is rather constant in the second stage, and rapidly increases in the third stage. These stages are illustrated in Fig. 93. Increase in stress increases the elongations and the rates of creep. The curves show that the duration of each stage of creep tends to decrease with increasing stress, but that fracture will not necessarily occur soon after the third stage of creep is entered. The specimen under 4000-pounds-per-square-inch stress was still in the second stage at 14,000 hours.

273. Effect of High Temperature on Ductility. The reduced ductility of 0.15 per cent carbon steel subjected to a temperature of 538° C. (1000° F.) is shown in Table XXVIII. This low ductility of carbon steel is explained by the formation of oxide between the grains at the surface of the specimens which is illustrated in the photomicrograph of Fig. 94. Progressive deterioration of the surface due to this intergranular oxidation with respect to time was noted.

A similar decrease in ductility of chromium-silicon-molybdenum alloy steel was not observed, however, as is shown by the results in Table XXVIII. None of the fractured creep specimens possessed as high ductility as the short-time tension specimen, but the amount of decrease was not so pronounced as for carbon steel. Furthermore, the ductility of

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* A. E. White, C. L. Clark, and R. L. Wilson: Influence of Time at 1000° F. on the Characteristics of Carbon Steel, *Proc. Am. Soc. Test. Mats.*, v. 36, Part II, 1936.

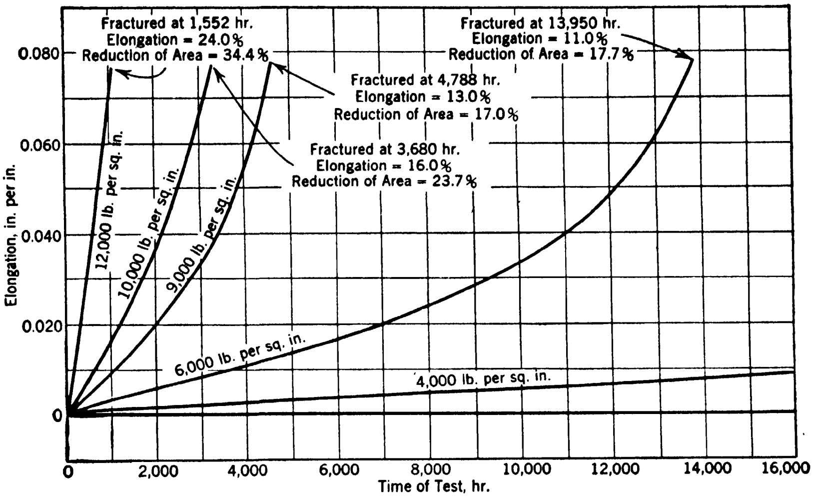

FIG. 92.—Time-elongation Curves at 538° C. (1000° F.) for Annealed Electric-furnace Carbon Steel. (Courtesy of A. E. White, C. L. Clark, and R. L. Wilson.)

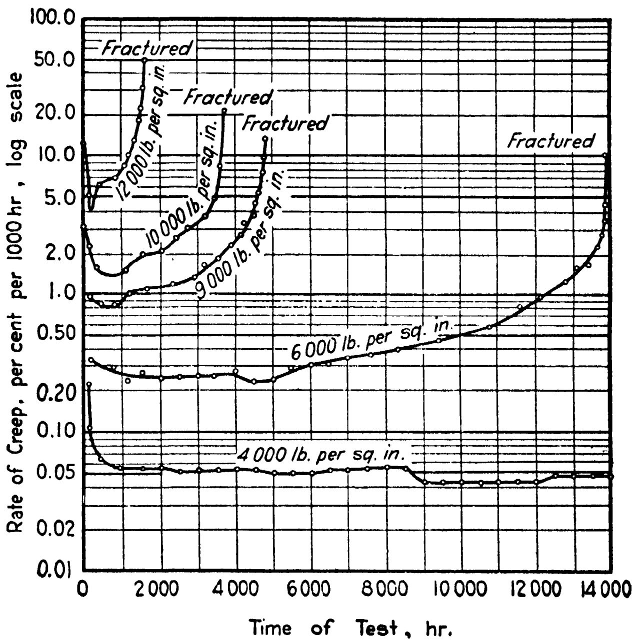

FIG. 93.—Influence of Time of Test on the Observed Creep Rate of Annealed Electric-furnace Carbon Steel at 538° C. (1000° F.). (Semi-logarithmic Coördinates.) (Courtesy of A. E. White, C. L. Clark, and R. L. Wilson.)

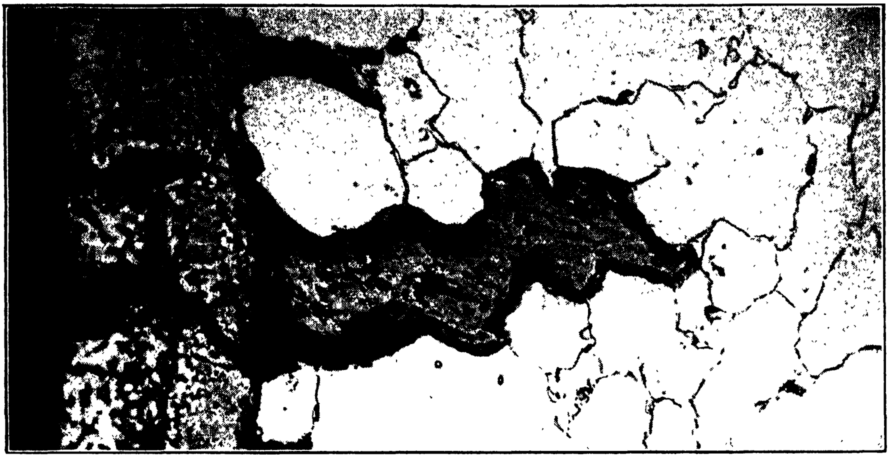

FIG. 94.—Microstructure of Surface Section of Creep Specimen Showing Intergranular Oxidation (1000×). (Courtesy of C. L. Clark.)

Annealed 0.15 C. electric-furnace steel. 12,000 lb. per sq. in., 1552 hr. for rupture.

this alloy steel did not decrease progressively as the testing time was increased. This alloy steel did not show intergranular oxidation.

TABLE XXVIII

INFLUENCE OF TIME AT 538° C. (1000° F.) ON DUCTILITY OF STEELS

Type of Steel	Ultimate Tensile Stress, lb. per sq. in.	Time for Rupture, hr.	Elongation, per cent in 2 in.	Reduction of Area, per cent
Annealed 0.15% C electric-furnace steel	Short-time tension specimen	.....	42.5	76.9
	12,000	1,552	24.0	34.4
	10,000	3,680	16.0	23.7
	9,000	4,788	13.0	17.0
	6,000	13,950	11.0	17.7
Alloy steel: Cr 1.25, Si 0.72, Mo 0.52, C 0.07, Mn 0.42	Short-time tension specimen	.....	32.5	78.6
	34,000	2,625	25.0	70.3
	30,000	3,250	21.0	67.9
	24,600	6,151	28.5	72.8

274. Type of Fracture. Fracture at 538° C. (1000° F.) in the short-time tension test of 0.15 per cent carbon steel is transcrystalline as shown in Fig. 95 (*a*). Both the ferrite and pearlite grains are distorted and elongated parallel with the axis of the specimen. This indicates that considerable strain-hardening occurred during the test with little if any recrystallization.

The fracture of the carbon-steel specimen subjected to creep for 4788 hours at 538° C. (1000° F.) showed a lack of strain-hardening as illustrated in Fig. 95 (*b*). The fracture is intercrystalline, and the grains are small and equi-axed and are thus free from strain. This type of fracture would be expected only when the temperature is above the lowest temperature of recrystallization of the metal.

275. Creep Limit. Creep limit is the stress allowable in a metal when subjected to a given temperature which will keep the deformation within a given limit in a certain number of years. Since it is not feasible to conduct creep tests at various temperatures and stresses over periods of a number of years on all metals before using them, the determination of a creep limit by extrapolation of data extending into the second stage is proposed by P. G. McVetty.* Referring to Fig. 93 it may be seen that the rate of creep in the second stage is practically constant for the stress of 4000 pounds per square inch. Since this creep curve is typical of creep curves for actual working stresses for many metals, the assumption that the creep curve in the second stage approaches a straight line is sufficiently accurate for many purposes, according to McVetty. He proposes the formula $\epsilon = \epsilon_0 + Vt$, where ϵ = final deformation in inches per inch, ϵ_0 = deformation at end of first stage in inches per inch, V = rate of

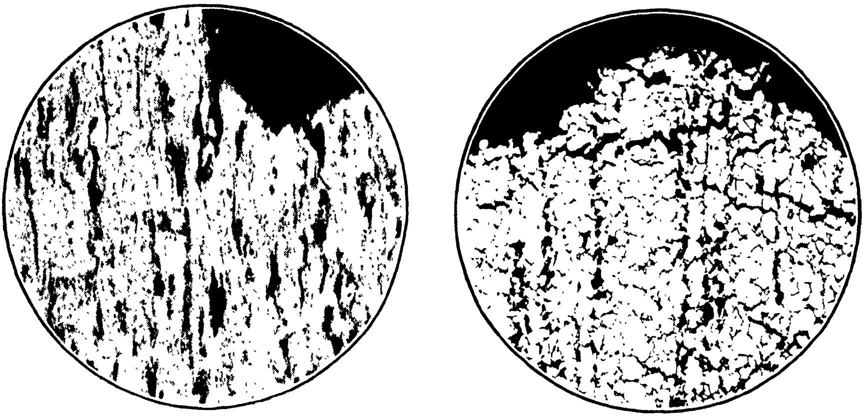

FIG. 95(*a*).—Short-time Tension Specimen. Note strain-hardening and transcrystalline fracture.

FIG. 95(*b*).—Creep Specimen. 9000 lb. per sq. in., 4788 hr. for rupture. Note intercrystalline fracture, and lack of strain-hardening.

FIG. 95.—Microstructures of Short-time Tension and Creep Specimen Fractures Showing Influence of Time on Type of Fracture Obtained on Annealed 0.15% C Electric-furnace Steel (100×.) (Courtesy of C. L. Clark.)

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* P. G. McVetty: The Interpretation of Creep Tests, *Proc. Am. Soc. Test. Mats.*, v. 34, Part II, 1934.

creep during the second stage in inches per inch per hour, and t = time in second stage in hours. Tests conducted at different stresses for a given temperature can be thus extrapolated and a series of curves can be drawn for the benefit of designers so that the creep limit corresponding to a maximum deformation for an expected service life under a certain temperature condition can be readily found. Obviously many objections can be raised against such a procedure, but it is a valuable method for organizing and correlating the results of creep tests.

IMPACT TESTING

276. General. The methods of impact testing are described in Chapter II. In this section the theory of impact tests and their use in selecting and inspecting metals are described.

277. Object of Impact Testing. The object of an impact test should be to determine whether a metal has resistance to failure due to brittleness under service conditions in a machine or structure. An impact test of metals should not be considered merely as a simulation of shock in service, but should be used as a control test even for metals that will not be subjected to impact stresses in service.

278. Cold Brittleness. Failure due to brittleness often occurs when ferrous metals become cold brittle. *Cold brittleness* refers to the change from a ductile fracture having a "silky" texture to a fracture exhibiting a granular structure that takes place in ferrous metals; it is accompanied by a decrease in the work required to cause failure. Cold brittleness does not refer to any particular temperature range since it is a condition dependent upon state of stress, velocity of deformation of the specimen, size of specimen, influence of notches in the specimen, carbon content of the steel, heat treatment, and cold work, as well as temperature.

Most non-ferrous metals do not exhibit cold brittleness to the same degree as steel. This is probably due to the different space lattice of non-ferrous metals as illustrated by the face-centered cubic arrangement compared to the body-centered cubic structure of alpha iron. Tin and zinc, however, show cold brittleness; this is probably associated with an allotropic change in the metal.

279. Type of Specimen. Impact tests are made both in flexure and in tension. The standard notched bars for the flexure type of test as used in the Charpy and Izod machines are illustrated in Figs. 5 and 6. Unnotched bars are seldom used in flexure. In tension impact testing, both notched and unnotched specimens are employed. These tension impact specimens have not been standardized but are preferred to the flexure type by many investigators because errors in machining are usually smaller than for the flexure test bars. When errors are made in machining notches, the resultant energy values become more a measure of local structural conditions than of the true dynamic properties of the metal.

280. Notched-bar Impact Testing. The effect of notches in bars is to modify the stress distribution and to set up a highly localized concentration of stress at the root of the notch. Furthermore, notched bars of certain ductile steels break off sharply when tested by impact, exhibiting a brittle fracture of crystalline appearance, whereas in the ordinary tension test the same steels fail with the usual silky texture of the fracture characteristic of a ductile steel. Other ductile steels are tough and deform appreciably in the same notched-bar impact test.

The type, sharpness, and depth of notches have a direct bearing on brittleness as indicated both by fractures and by impact resistance.

281. Effect of Temperature upon Brittleness. Temperature has a much more marked effect on the cold brittleness of steel than upon tensile properties. Brittleness as determined in notched-bar impact tests may change abruptly with temperature change. The temperature corresponding to this abrupt change is dependent both upon the form and size of notch as well as upon the properties of the steel. Some steels show this sudden decrease in impact resistance at normal room temperature, which explains why it is often difficult to check results of energy absorbed on duplicate specimens. Tests are readily reproducible, however, in those ranges of temperature where no sudden changes in impact resistance occur.

If the steel is to be used at a low temperature, the impact tests should be performed at this temperature because a high impact value at normal temperature is no insurance of ductile behavior at lower temperatures.

Cold brittleness exhibited by tests on notched specimens of steel at subnormal temperatures may not be shown by tests on unnotched specimens. This phenomenon has been observed by Professor O. H. Henry in the testing of welded unnotched steel specimens in tensile impact.

282. Effect of Velocity of Deformation. The pendulum of the ordinary impact-testing machine strikes the specimen with a relatively low velocity of deformation. It has been found that increasing the velocity of deformation affects the energy absorbed at different temperatures. It has been shown that high-velocity tests are essential to reveal the true dynamic properties of metals. For example, it has been found by Jenks, Mann, and Haskell at the Watertown Arsenal that steels which are similar in impact properties at low velocities may behave differently at high velocities, some showing extreme brittleness. More research is needed at high velocities of deformation to determine dynamic properties of metals.

283. Selection of Ferrous Metals. Steels from different mill heats of the same typical chemical composition and almost duplicate tensile-strength properties may possess strikingly different notched-bar impact values as shown in Table XXIX, which gives results reported by Riegel and Vaughn. These authors have reported that notched-bar impact testing made it possible to select between satisfactory and unsatisfactory steels for heavily stressed gears and pinions of tractors when tensile strength and chemical composition showed no appreciable differences. Freedom from failures of tractor parts in service closely paralleled the classification made on the basis of notched-bar impact tests. Riegel and Vaughn conclude that the notched-bar impact test is useful in evaluating the quality of ferrous metals, even though the material is not called upon to resist impact stresses in service, and that it is a discriminating proof of the quality of heat treatment of ferrous metals.

TABLE XXIX

STEEL QUALITY SHOWN BY IMPACT TESTS[1]

	Carbon, per cent	Manganese, per cent	Sulfur, per cent	Phosphorus, per cent	Silicon, per cent	Nickel, per cent
Mill heat A.	0.46	0.61	0.031	0.016	0.20	3.57
Mill heat B.	0.47	0.70	0.036	0.018	0.24	3.55

Physical Properties (Drawn at 425° F. for 1½ hr.)

	Rockwell Hardness, "C" Scale	Tensile Strength, lb. per sq. in.	Yield Point, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Charpy Impact, ft-lb.	Tension Impact (notched specimen), ft-lb.
Mill heat A (good)...	52	278,000	214,000	11.5	44.3	18.0	62
Mill heat B (poor)....	53	288,500	214,500	11.5	34.1	5.5	9

[1] Riegel and Vaughn: *Proc. Am. Soc. Test. Mats.*, v. 38, Part II, 1938.

It is questionable whether, at this stage in the development of the impact test, selection between different classes of ferrous metals can properly be made on the basis of energy values obtained in impact testing. Furthermore, actual notched-bar impact results are of no direct value in designing.

The type of fracture obtained, whether crystalline or ductile, is considered to be of more importance than the actual value of energy absorbed in fracturing the specimen in foot-pounds.

For further information on impact testing, reference should be made to the Symposium on Impact Testing, *Proceedings of the American Society for Testing Materials,* v. 38, Part II, 1938.

WEAR

284. Characteristics of Wear. Wear of metal is produced by contact with other materials. Usually the term "wear" is associated with abrasion. A worn metal part many times appears to have small fractures on its surface and if the metal is ductile may have its shape distorted owing to plastic flow. Oxide films formed on metallic surfaces may be worn off by abrasion.

When ductile steels rub against each other, particles of soft metal may come into contact and become displaced, causing the formation of pits in the surfaces. Pitting is not so likely to occur when steel is in contact with brittle metal or when steel shafts are in contact with a bearing metal such as babbitt metal. Increased wear and pitting may be caused by increase in temperature of the rubbing metals.

285. Accelerated Wear Tests. Attempts have been made many times to determine the wearing properties of materials by means of accelerated tests. Such tests usually consist of abrasion tests where one material is rubbed against another under given conditions of load and velocity. Poor correlation has been found to exist between the results of many of these accelerated tests and actual service results. Furthermore, when materials are tested by various wear tests, some materials show up well under some tests and poorly in others. These difficulties are due in part to the difficulty in simulating service conditions of load application, velocity, and nature of abrading surface in accelerated wear tests. There is need for research on wear tests for many materials of construction.

CORROSION

286. Corrosion in General.* *Corrosion* may be defined as the conversion of metals by natural agencies into compound forms. *Rusting* refers to the corrosion of iron and steel.

Corrosion of metals is a problem of great industrial importance not only on account of the wastage involved but also because of the limited services rendered under certain conditions of exposure by several common metals, particularly iron and steel, which otherwise have good physical properties.

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*F. N. Speller: Corrosion-resistant Metals, *Mechanical Engineering,* December 1936.

The common metals are relatively unstable in that they tend to revert with a decrease in free energy of the system to the more stable compounds such as oxides and carbonates, in which form they are found in nature.

The different types of corrosion may be classified according to environment as atmospheric, underwater, soil, chemical, and electrolysis due to stray electric currents. In atmospheric corrosion there is an excess of oxygen available so that the predominant factor is moisture. In underwater corrosion the concentration of dissolved oxygen is the predominant factor. In soil corrosion the principal factors are electrical conductivity, total acidity, and water content. Chemical corrosion depends largely upon the chemical compounds in contact with the metal surfaces. Electrolysis due to stray electric currents may cause severe corrosion.

287. Electrolytic Theory. The electrolytic theory of corrosion of metal is generally accepted. According to this theory, metal passes into solution as ions, and the metallic ions give up their electric charge in escaping from solution and forming metal again. This theory extends the operation of Faraday's law as applied to the voltaic cell to the corrosion of metals. In a voltaic cell the passing of an electric current through an electrolyte is associated with the dissolving of a certain amount of material from the anode and the depositing of a chemically equivalent amount at the cathode. In the process of corrosion, adjacent areas on the surface of the metal become anodes and cathodes. Electrolytes such as water, aqueous solutions, or moist air in contact with the metal connect the anodes and cathodes and establish numerous small cells. The driving force in these cells is the solution pressure of the corroding metal.

Anodic and cathodic areas may be caused by differences in metal composition, structural homogeneity, surface finish, mechanical strain, inherent power to form surface films, and by unequal concentration of oxygen on different parts of the surface.

288. Primary and Secondary Reactions. There are two main steps in the reactions which occur when corrosion takes place on metal in contact with water: first, the primary reactions due to the initial tendency of the metal to enter solution; and second, the secondary reactions which control the rate of deterioration. The initial rate of reaction is likely to be quite rapid but is soon retarded by the formation of films of hydrogen or other corrosion products on the surface of the metal. The formation of these protective films may in time render the metal passive. The secondary reactions have to do with the breaking down of these protective films and hence tend to cause corrosion.

In the presence of water, the metal enters the solution at anodic areas and an equivalent amount of hydrogen is deposited at adjacent cathodic areas, forming a polarizing film and thus in time making the metal passive. If free oxygen or oxidizing compounds combine with hydrogen, the polarizing film of hydrogen on the cathodic areas is removed and corrosion will occur since the primary reaction can continue.

Many illustrations of the effect of dissolved oxygen upon corrosion can be given. Iron which is alternately wet and dry tends to corrode faster than iron which is continually wet because both water and oxygen are present in plentiful amounts. Plumbing systems tend to corrode owing to the changing of the water and consequent replenishment of the oxygen. The flow of water in open channels in a hydraulic laboratory increases the supply of oxygen and causes increased corrosion in pipes and tanks through which the water flows.

If oxygen is not available for this depolarization, corrosion is reduced to a negligible amount in water that is alkaline or only slightly acid, but if the acidity is sufficient to cause evolution of gaseous hydrogen, more metal can be dissolved.

289. Pitting. Pitting is caused mainly by contact with dissimilar metals or other material on the surface. Blisters of rust are formed and the pits under the blisters are kept anodic since no oxygen can come in contact. The relatively large cathodic areas have their hydrogen films rapidly depolarized by oxygen which causes the metal in the pits to go into solution with increased intensity. Such action can cause rusting completely through thin sections of metal in a short time.

The presence of mill scale on steel, deposits of corrosion products or of foreign matter, cracks or angles in the structure which interfere with diffusion are likely to cause the formation of active cells at such spots on the metal due to variations in oxygen concentration. The metal surface should be kept clean to prevent this form of corrosion.

290. Corrosion of Pipes. A thin stationary film of water is maintained on the surface of pipes carrying water. It is necessary for free oxygen to penetrate this stationary film in order to depolarize hydrogen films. Corrosion is less for laminar flow conditions when the velocity of the water is low than for turbulent flow conditions at velocities above the critical velocity. It is thought that this is due to the decreased thickness of the stationary film of water at the higher velocities. At high velocities in turbulent flow the formation of ferric protective films may be promoted, causing a decrease in corrosion.

A continuous coating on the inside surface of pipes reduces corrosion since oxygen has to penetrate the coating in order to react with hydrogen on the cathodes. Coatings such as sodium silicate, mud, ferric hydrogel deposited from dissolved ferrous hydroxide, and deposits from sulfates and bicarbonates in water may tend to prevent depolarization of hydrogen films by oxygen.

291. Effect of Corrosion on Endurance Limit. Water corrosion has been known to reduce the endurance fatigue limit of carbon and alloy steels from one-half the tensile strength to as low as 12,000 pounds per square inch. Special precautions should be taken to protect parts from corrosion when under high cyclic stresses.

292. Effect of Temperature on Corrosion. Oxidation at elevated temperatures may occur by direct chemical reaction between air and metal (Art. 273). Water corrosion is increased as the temperature is increased owing to decreased viscosity of water which tends to increase oxygen diffusion. In pressureless containers the worst condition is reached at about 85° C. (185° F.).

293. Preventive Measures. Preventive measures against corrosion may be divided into three classifications according to the principle employed: (1) paints, varnishes, lacquers, and other applied coatings (see Chap. XXII); (2) treatment of liquids coming into contact with the metals as by the addition of chemicals to the liquids to assist in forming a natural protective layer on the metal surface; and (3) the use of metals that have the power to form self-healing protective films with the particular environment under consideration.

QUESTIONS

1. What is meant by "slip"?

2. Describe the behavior of metals under repeated stresses.

3. What is the character of the fracture of steel cylindrical shafts which fail under alternating cycles?

4. Sketch an *S-N* diagram.

5. How is the endurance limit of steels determined? Is it a definitely fixed value? Explain.

6. How may the presence of fatigue cracks be ascertained?

7. What is meant by "overstressing" in fatigue? By "understressing"?

8. May overstressing in fatigue cause damage to a metal? Explain.

9. State typical endurance ratios for rolled steel, wrought iron, cast steel, and cast iron with respect to ultimate tensile strength.

10. Describe the characteristics of the three stages of creep.

11. What is the effect on ductility caused by stressing carbon steel under high-temperature conditions for long periods of time? How may this effect be explained?

12. Describe the differences in type of fracture obtained in instantaneous tension tests and long-time creep tests at an elevated temperature of 538° C. (1000° F.) for a 0.15 per cent carbon steel.

13. Describe the essential features of McVetty's method of determining creep limit.

14. For what purposes may impact tests be conducted on metals?

15. What is "cold brittleness"?

16. Discuss the characteristics of wear of metals.

17. Discuss briefly the correlation of accelerated wear tests with actual service conditions.

18. Discuss the importance of preventing corrosion of metals.

19. Describe the electrolytic theory of corrosion of metal.

20. Discuss the effect of secondary reactions upon corrosion.

21. Why may aeration of water in a hydraulic laboratory increase corrosion in pipes?

22. What causes pitting?

23. Describe the corrosion of pipes carrying flowing water.

24. What is the effect of corrosion on fatigue resistance of carbon steel?

25. Discuss the prevention of corrosion of metals.

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SECTION 3

CEMENTING MATERIALS

INTRODUCTION

294. Classification of Cementing Materials.*

(*A*) Simple Cementing Materials: including all those cementing materials which are produced by the expulsion of a liquid or gas, through the action of heat, from a natural raw material, and the setting properties of which are due to the simple reabsorption of the same liquid or gas, and the reassumption of original composition; the set cement being, therefore, similar in chemical composition to the raw material from which it was derived.

- (1) Hydrate Cementing Materials or Plasters: manufactured by driving off water from gypsum; setting properties due to the reabsorption of water.
  - Plaster of Paris.
  - Gypsum plasters.
  - Cement plasters.
  - Dead-burned plasters.
  - Hard-finish plasters.
- (2) Carbonate Cementing Materials or Limes and Magnesia: manufactured by driving off carbon dioxide from limestone or magnesite; setting properties due to the reabsorption of carbon dioxide.
  - Limes.
  - Magnesia.

(*B*) Complex Cementing Materials: including all those cementing materials the setting properties of which are due to the formation of entirely new chemical compounds during manufacture or use; the set cement being, therefore, different in chemical composition from the raw material or mixture of raw materials from which it was derived.

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* Eckel: "Cements, Limes, and Plasters."

(1) Silicate Cementing Materials or Hydraulic Cements: setting properties due entirely or largely to the formation of silicates during the process of manufacture or use.

  - Hydraulic limes.
  - Grappier cements.
  - Puzzolan cements.
  - Slag cements.
  - Natural cements.
  - Portland cements.
  - Portland-puzzolan cements.
  - Alumina cements.

(2) Oxychloride Cementing Materials: setting properties due to the formation of oxychlorides.

  - Magnesia cements.
  - Flooring cements.
  - Stucco.

CHAPTER XIII

GYPSUM PLASTER

295. Definition and Classification. Gypsum plasters comprise all that class of plastering and cementing materials which are obtained by the partial or complete dehydration of natural gypsum, and to which certain materials that serve as retarders or hardeners, or that impart greater plasticity to the product, may or may not have been added during or after calcination. Gypsum plasters may be classified as follows.*

(*A*) Produced by the incomplete dehydration of gypsum, the calcination being carried on at a temperature not exceeding 190° C. (374° F.).
- *Plaster of Paris,* produced by the calcination of a pure gypsum, no foreign materials being added either during or after calcination.
- *Cement plaster* (often called *patent* or *hard wall plaster*), produced by the calcination of a gypsum containing certain natural impurities, or by the addition to a calcined pure gypsum of certain materials which serve to retard the set or render the product more plastic.

(*B*) Produced by the complete dehydration of gypsum, the calcination being carried on at temperatures exceeding 190° C. (374° F.).
- *Flooring plaster,* produced by the calcination of a pure gypsum.
- *Hard-finish plaster,* produced by the calcination, at a red heat or over, of gypsum to which certain substances (usually alum or borax) have been added.

296. Gypsum Rocks. Pure gypsum is a hydrous lime sulfate ($CaSO_4 + 2\,H_2O$), the composition of which by weight is:

Lime sulfate ($CaSO_4$)	Lime (CaO)	32.6%	79.1%
	Sulfur trioxide (SO_3)	46.5	
Water (H_2O)			20.9
			100.0%

Natural deposits of gypsum are very seldom pure, the lime sulfate being adulterated with silica, alumina, iron oxide, calcium carbonate, and magnesium carbonate. The total of all impurities varies from a very small amount up to a maximum of about 6 per cent.

The physical form of a natural gypsum is usually that of a massive rock formation. It also occurs as an earthy gypsum or gypsite, and as

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* Eckel: "Cements, Limes, and Plasters."

gypsum sands in some localities. Alabaster is a specially pure white massive gypsum of very even texture and fine grain, and selenite is a white semi-transparent crystalline gypsum which occurs only in relatively small deposits in massive gypsum.

MANUFACTURE OF GYPSUM PLASTERS

297. General. Three operations are involved in the process of manufacturing plaster: crushing, grinding, and calcination. Rock gypsum is crushed to fragments about one inch in diameter, which are passed through an intermediate crusher and then pulverized in a finishing mill. The ground gypsum is then calcined in kettles or in rotary kilns.

298. Theory of Calcination. If pure gypsum is subjected to any temperature above 100° C. (212° F.), but not exceeding 190° C. (374° F.), three-fourths of the water of combination originally present is driven off. The resultant product is called *plaster of Paris* ($CaSO_4 + \frac{1}{2} H_2O$). Since the time required for the process is directly dependent upon the temperature maintained, it is the general practice to keep the temperature near the highest possible limit, thus effecting an economy in both time and fuel. Plaster of Paris readily recombines with water to form gypsum, hardening in a very few minutes.

If the gypsum is calcined at temperatures much above 190° C. (374° F.) it loses all its water of combination, becoming an anhydrous sulfate of lime ($CaSO_4$). All temperatures exceeding that required for complete dehydration result in some impairment, temporary or permanent, of the capacity of the plaster for recombination with water, the extent of the injury being dependent upon the intensity and the time of the heating and upon the state of subdivision of the material. If the material is finely divided, the plaster may be made totally incapable of recombining with water (dead-burned plaster). If the material is calcined in a lumpy condition, the temperature not exceeding 500° C. (932° F.) and not prolonged beyond three or four hours, the principal effect upon the product is a great retardation of the rate of setting and hardening, a hydrate being ultimately formed, in the course of days or weeks, which greatly exceeds ordinary plaster in hardness and strength.

299. Practice of Calcination. Plaster of Paris and cement or hard wall plasters are made in practically the same manner, the difference in their properties being due to the use of comparatively pure gypsum for the first substance, and impure or adulterated gypsum for the second. Plaster is calcined in kettles or rotary kilns. The kettle is a cylindrical steel vessel, 8 to 10 feet in diameter and 6 to 9 feet high, mounted upon a masonry foundation. The bottom is convex and made of cast iron. A masonry wall encloses the steel cylinder, leaving an open annular space between for the circulation of heat. A fire is maintained on grates below the kettle, and the heated gases pass through ports into the open annular space, then through the kettle in horizontal flues and out through the stack. A central vertical shaft propels paddles just above the bottom, thus keeping the material agitated and preventing the burning out of the bottom.

The charge, consisting of 7 to 10 tons of ground gypsum, is delivered by a chute to the charging door provided in the sheet-iron cap of the kettle. Heat is gradually applied as the charge is slowly fed in, and, as the temperature rises after charging is complete, the contents boil violently until the mechanically held water is driven off as steam. If the temperature is held at about 160° C. (329° F.) the material settles down in a quiescent state, and if the calcination is stopped at this point the resulting product is known as "first settle" gypsum. If the temperature is raised, boiling is renewed when the water of combination begins to be driven off. If the temperature is held at about 205° C. (401° F.) the material settles down a second time and the result is "second settle" gypsum. The kettle is discharged by blowing out through a small gate in the lower part of the side of the shell.

When the rotary calciner is employed the raw material is used in the condition in which it comes from the intermediate crusher, and feeding from the supply bin is continuous.

The cylinder of the calciner is set on a slight incline, and the lumpy material fed in at the upper end gradually traverses its length as the cylinder slowly rotates, is discharged at the lower end, and enters calcining bins lined with non-absorptive brick.

The heat attained in the rotary calciner is from 200° C. (392° F.) to 300° C. (572° F.), but time does not suffice for the complete dehydration of the gypsum, and the removal of combined water is completed in the calcining bins through the agency of the residual heat of the material itself. After about thirty-six hours the process will be completed. Air inlets are then opened and the contents of the bin are rapidly cooled. By providing four bins for each calciner the process is made continuous; while one bin is being charged, the process of calcination is being completed in the second and third bins, and the fourth is being discharged. The product of the calcining bins is conveyed to finishing mills and there pulverized to the form of the marketable article.

Many cement or hard-wall plasters are made directly from earthy gypsum or gypsite, which is often found to contain a suitable percentage of foreign matter of such character that no corrective material need be added either to retard the set or to impart plasticity.

Flooring plaster is usually produced by the calcination of a comparatively pure gypsum in a lump form in a vertical separate-feed kiln which differs little from the separate-feed kiln used for the calcination of lime. The fuel, burned on grates outside the kiln, does not come in contact with the gypsum, but the hot gaseous products of combustion pass directly through it, heating it to a temperature of 400° C. (752° F.) to 500° C. (932° F.). Higher temperatures, or prolongation of heating beyond 3 or 4 hours, ruin the plaster by robbing it of its setting properties as above noted. Fine pulverization of the plaster must follow calcination.

A well-known variety of hard-finish plaster is the so-called *Keene's cement.* This plaster is produced by the double calcination of a very pure gypsum. After the lump gypsum has been calcined at a red heat, the resulting anhydrous lime sulfate is immersed in a 10 per cent alum solution, then recalcined, and finally pulverized in a finishing mill.

300. Additions Subsequent to Calcination. Plaster of Paris is seldom adulterated in any way during manufacture, but cement or hard wall plasters often require the addition of a retarder to render them sufficiently slow-setting. The usual retarders are organic materials, such as glue, sawdust, blood, or packing-house tankage. As a rule the amount of retarder required does not exceed 0.2 per cent. The theory of the action of retarders is that they keep the molecules of the plaster from too close contact and thus delay crystal growth.

Certain very impure gypsums produce a plaster which is too slow-setting, or sometimes extreme rapidity of set is required. For such gypsums the addition of an accelerator is necessary. The materials used for this purpose are crystalline salts, common salt ($NaCl$) being one of the best.

Gypsum plasters destined for use as wall plasters must usually have their plasticity enhanced by the addition of some material such as clay or hydrated lime, through the agency of which the naturally "short," non-plastic material is greatly improved in working qualities and sand-carrying capacity. With the exception of those plasters made from earthy gypsum, which naturally contains 20 per cent or more of clay, it is the usual practice to add about 15 per cent of hydrated lime or, less frequently, clay, to the calcined plaster. Greater cohesiveness may also be imparted to wall plasters by the addition of finely picked hair or shredded wood fiber.

No additions are made to flooring plaster subsequent to calcination. Keene's cement is treated with an alum bath as above noted. Mack's cement, another variety of hard-finished plaster, is made by the addition to dehydrated gypsum (flooring plaster) of 0.4 per cent of calcined sodium sulfate (Na_2SO_4) or potassium sulfate (K_2SO_4).

PROPERTIES AND USES OF GYPSUM PLASTERS

301. Setting and Hardening.* The setting of plaster of Paris and other gypsum plasters is a process of recombination of the partly or totally dehydrated lime sulfate with water to reform hydrated lime sulfate or gypsum. A pure plaster of Paris sets within 5 to 15 minutes after the addition of water. Plasters made from impure gypsum are less quick-setting, requiring from 1 to 2 hours, and the completely dehydrated classes of plasters are very slow-setting, whether adulterated or not. The ultimate degree of hardness attained by impure cement or hard wall plasters greatly exceeds that of pure plaster of Paris, and the hard-burned plasters are hardest of all.

302. Strength of Plasters. The tensile and compressive strengths of plaster are dependent upon many considerations incidental to methods and conditions of testing. Available results of many tests of neat plasters prepared and tested under reasonable conditions indicate tensile strengths varying from 50 to 500 pounds per square inch and compressive strengths of 800 to 2200 pounds per square inch.

The gain in strength is very rapid for the first few days and the maximum strength is attained in a few weeks, after which retrogression in strength usually occurs.

The strength of mortar is dependent upon the character of the sand used. Mortar made from fine plaster is somewhat stronger than that made from plaster not sifted.

303. Uses of Various Gypsum Plasters. Plaster of Paris, because of the extremely rapid set which especially fits it for various special applications as a casting plaster, etc., finds very little application as a material of engineering construction. Almost its only structural use is in the form of molded ornaments of "stucco" which serve as architectural adornment of buildings. Plaster of Paris is not adapted for use as either a wall plaster or a mortar for masonry construction unless additions are made to retard its set and make it more workable. If this is done, however, it is no longer called plaster of Paris, but becomes a cement or hard wall plaster.

Cement or hard wall plasters find their principal applications as wall plasters with which a certain amount of hair, wood fiber, or asbestos fiber, together with hydrated lime or clay, has been mixed at the place of manufacture.

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* By the term "setting" is meant the initial loss of plasticity, while "hardening" means the subsequent gain in strength and in ability to resist indentation or abrasion.

The American Society for Testing Materials specifies the composition of ready-sanded gypsum plasters as follows:

	SCRATCH OR FIRST COAT	BROWNING OR SECOND COAT
Sand (by weight)	Not more than ⅔	Not more than ¾
Calcined gypsum	Not less than 20%	Not less than 15%

The remainder, in each case, may consist of materials added to control the working qualities, setting time, and the fibering.

Gypsum wall plasters possess certain advantages over ordinary lime plasters, but also suffer by comparison with lime plasters in other respects. Among the advantages of gypsum plasters is the fact that the material comes upon the work ready to be mixed with sand and water and immediately applied to the lath, whereas quicklime requires careful slaking and should be allowed to season before being made up in a mortar and applied to the walls. Gypsum plasters set more rapidly and dry out in a much shorter time than lime plasters, thus often avoiding a delay in the completion of the interior finish of buildings. On the other hand, no gypsum product makes as plastic and smooth working a plaster as does the best lime, provided the lime is properly slaked, seasoned, and mixed. Lime plasters excel in sand-carrying capacity, making it possible to use more sand than with most gypsum plasters.

Among the other applications of hard wall plaster the following may be mentioned: Mixed with cinders or crushed stone and water to form a workable mix ("gypsum concrete"), hard wall plaster is poured in forms for floor or roof panels for buildings. Mixed with sawdust it is molded into blocks which may be nailed in place as a wall finish, and, without the sawdust, it may be molded into solid or hollow building blocks and tiles for the construction of partition walls and floors and for fireproofing. Another application of gypsum plaster is in the construction of "plaster board" and "wall board" wherein the plaster is laminated with thin layers of cardboard, wood, or other material in sheets which are ready to be nailed to the studding of partition walls. The wall surface if made of plaster board is subsequently plastered, but if made of wall board may be finished in panels with no additional plaster by simply covering the joints with wood strips.

Flooring plaster, as the name implies, is intended primarily as a surface finish for floors. It must be protected from moisture while setting, and must dry evenly to avoid the formation of cracks. After standing about 12 hours it is pounded with wooden mallets and smootned with trowels. It is seldom used in the United States.

Hard-finished plasters find their principal application as wall plasters and as floor surface, especially as an imitation of tiling or marble for floors and wainscoting in hospitals, lavatories, etc. Keene's cement is, perhaps, the best-known variety of hard-finish plaster. Its set is extremely slow, and it gains in strength very gradually, but ultimately attains a great degree of hardness and a strength exceeding that of any ordinary gypsum plaster. It may be regauged with water after having become partly set, and will then take its set and harden just as satisfactorily, apparently, as if the process of hardening had not been interrupted.

Gypsum often serves as a fireproofing material, although its strength is destroyed by long-continued heat. The water of crystallization is driven off and the surface reduced to a powder which, if not removed, acts as an insulator and protects the gypsum inside.

304. Tests for Gypsum Products. Standard methods of testing gypsum have been adopted by the American Society for Testing Materials to govern the determination of free water, fineness, chemical analysis, consistency, water-carrying capacity, dry bulk, wet bulk, time of set, tensile strength, and compressive strength; and in addition, definite specifications covering the physical properties of certain gypsum products have also been adopted by the Society.

A few examples of these specifications are shown in Table XXX.

TABLE XXX

A.S.T.M. SPECIFICATIONS FOR GYPSUM PRODUCTS

Gypsum Plasters

Type of Plaster	Wood-fibered *W*	Neat *N*	Sanded Brown Coat *B*	Sanded Scratch Coat *S*
Content of $CaSO_4, \frac{1}{2}H_2O$, minimum, per cent	48.5	51.5	15.0	20.0
Content of wood fiber, minimum, per cent	1.0	....	....	....
Content of sand, maximum, per cent	....	....	75.0	66.7
Time of set, minimum, hours	1.5	1.5	2.0	1.5
Time of set, maximum, hours	8.0	....	6.0	7.0
Tensile strength, minimum, lb. per sq. in.	125.0	150.0	50.0	75.0

Calcined Gypsum or Plaster of Paris

Tensile strength	200 pounds per square inch
Compressive strength	1000 pounds per square inch
Time of set, for unretarded	Between 10 and 40 minutes
Time of set, for retarded	Between 40 minutes and 6 hours
Fineness	No residue on a No. 14 sieve and, for general use, between 40 and 75% must pass a No. 100 sieve

Plaster and Wall Board

The composition and dimensions of plaster and wall board are specified and also their transverse strength when tested with a center load and a 16-inch span. The test specimen is 12 inches wide and 18 inches long.

Gypsum Tile or Blocks

Compressive strength, dry	75 pounds per square inch
Compressive strength, saturated	Not less than 33⅓% of the dry strength

Blocks are also tested for rate of absorption and for fire resistance.

QUESTIONS

1. Name and define four kinds of gypsum plaster.

2. Describe briefly the manufacture of gypsum plaster.

3. Write the chemical equations for the manufacture and setting of plaster of Paris.

4. What is Keene's cement?

5. In the manufacture of a gypsum wall plaster, packing-house tankage, hair, clay, and sand were added subsequent to the calcination of a pure gypsum. Give the reasons for each of these additions.

6. What is the theory of the action of retarders?

7. What materials are used to accelerate the setting of gypsum plasters?

8. Why is hydrated lime many times mixed with gypsum plaster to form a wall plaster?

9. What advantages does gypsum plaster have over lime plaster?

10. What is plaster board? Wall board? Gypsum concrete?

11. Describe the fireproofing characteristics of gypsum products.

12. Name the principal tests specified for gypsum products.

13. What is the minimum compressive strength required for calcined gypsum? For dry gypsum blocks?

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CHAPTER XIV

LIME

305. Definition and Classification. *Quicklime* is the name applied to the common or commercial form of calcium oxide (CaO), obtained by the calcination of a stone in which the predominating constituent is calcium carbonate ($CaCO_3$), often replaced, however, to a greater or less degree by magnesium carbonate ($MgCO_3$), this product being one that will slake on the addition of water.

Hydrated lime is quicklime which has been chemically satisfied with water during manufacture.

Quicklime is divided into two general grades:

Selected. A well-burned lime, picked free from ashes, core, clinker, or other foreign material, containing not less than 90 per cent of calcium and magnesium oxides and not more than 3 per cent of carbon dioxide.

Run-of-kiln. A well-burned lime without selection, containing not less than 85 per cent of calcium and magnesium oxides and not more than 5 per cent of carbon dioxide.

According to the physical form of the material, quicklime is marketed as:

Lump Lime. The size in which it comes from the kiln.

Lump Lime Screened. Lump lime reduced in size to pass a ½-inch screen.

Pulverized Lime. Lump lime reduced in size to pass a ¼-inch screen.

According to relative content of calcium oxide and magnesium oxide, quicklimes are divided into four types:

High-calcium. Quicklime containing 90 per cent or more of calcium oxide (CaO). (Sometimes termed "rich," "fat," or "caustic" lime.)

Calcium. Quicklime containing not less than 85 per cent and not more than 90 per cent of calcium oxide.

Magnesian. Quicklime containing between 10 and 25 per cent of magnesium oxide (MgO or magnesia).

High-magnesian or *Dolomitic.* Quicklime containing more than 25 per cent of magnesium oxide.

Hydrated lime is commonly divided into four classes: *High-calcium*; *calcium*; *magnesian*; *high-magnesian.* The chemical composition is practically the same as for the corresponding classes of ordinary lime.

Hydrated lime for structural purposes is further classified as either masons' or finishing.

306. Limestone Rocks. An ideal, pure limestone consists entirely of calcium carbonate ($CaCO_3$), which, at a temperature of 900° C. (1652° F.) or over, becomes dissociated, the carbon dioxide (CO_2) being driven off as a gas, leaving behind a white solid, calcium oxide or quicklime (CaO).

As pure calcium carbonate consists of 56 parts by weight of CaO to 44 parts of CO_2, the theoretical proportion of quicklime obtainable by the calcination of limestone will be 56 per cent by weight.

In practice, the proportion of quicklime will always fall below this theoretical limit on account of the inevitable presence of impurities in the limestone and the imperfections of the process of calcination.

Limestones encountered in practice depart more or less from this theoretical composition. Part of the lime is almost always replaced by a certain percentage of magnesia (MgO), making the stone to a greater or less extent a magnesian limestone. In addition to magnesia, silica, iron oxide, and alumina are usually present and, to a slight extent, sulfur and alkalies.

The physical character of the limestone has an important bearing upon the burning temperature, quite aside from the question of chemical composition. A naturally coarse, porous stone is acted upon by heat much more rapidly than a dense, finely crystalline stone, and in consequence may be burned more rapidly and at a lower temperature. Small pieces of stone may also be burned more readily than large ones. Large sizes seem to be preferred, however, by the practical lime manufacturer, the common practice being to use stones measuring about 8 to 10 inches in diameter.

MANUFACTURE OF LIME

307. Theory of Calcination. The burning or calcination of lime accomplishes three objects:

> The water in the stone is evaporated.
>
> The limestone is heated to the requisite temperature for chemical dissociation.
>
> The carbon dioxide is driven off as a gas, leaving the oxides of calcium and magnesium.

The evaporation of any water present in the stone means that a certain portion of the heat supplied during calcination does not directly assist in the dissociation of the carbonates. This heat does not mean a thermal loss, however, because the presence of the water, and of the steam generated from it, facilitates the dissociation process.

The temperature of dissociation of pure calcium carbonate at a pressure of one atmosphere has been determined to be 898° C. (1650° F.), and the corresponding temperature for magnesium carbonate somewhat lower.

Theoretically, all limestones could be properly burned at a temperature of about 880° C. (1616° F.), provided sufficient time was allowed. In practice, however, the maximum kiln output is obtained by burning at a considerably higher temperature. The highest temperature practicable is not the highest temperature attainable, because the increased activity of the impurities with rising temperature sets a very definite maximum limit, the exceeding of which means serious injury to the quality of the lime produced.

The impurities in limestones readily combine with the basic lime and magnesia. The silica forms silicates, the alumina forms aluminates, and the iron oxide forms ferrites. These silicates, aluminates, and ferrites are all readily fusible compared with pure lime or magnesia, and the result of their formation is a softening of the portion of the stone thus rendered fusible at the practical dissociation temperatures; its softening envelops the particles of lime with a slag-like coating which causes the quicklime to slake with difficulty. The softening of the mass also results in compacting the material, thereby further injuring its qualities by mechanically rendering it less porous.

This behavior on the part of the impurities accounts for the existence of maximum temperature limits in burning impure limestones, and explains why the exceeding of these limits causes marked loss of power of the quicklime to combine with water in slaking, whereas it is practically impossible to overburn pure limestone.

Provision must be made for carrying off the carbon dioxide gas evolved during calcination. If this gas is allowed to accumulate it may recombine with lime and magnesia and reform their carbonate. This phenomenon is known technically as "recarbonating."

308. Practice of Calcination. The types of kilns employed in lime burning may be described as follows:

Intermittent Kilns. An early form of intermittent kiln consisted simply of a dome-like structure crudely constructed of the larger blocks of the stone to be burned. The balance of the limestone was piled on top and a wood fire started underneath. A bright red heat having been obtained throughout the mass of stone, this temperature was maintained for a period of 3 or 4 days, when, the mass having become soft, the fire was allowed to go out and, after cooling, the lime was removed, the structure being demolished in so doing.

Permanent intermittent kilns, often called "pot kilns," built of stone with a firebrick lining and provided with a grate upon which the fuel was placed, gradually replaced the original type. These kilns are provided with an arched opening at the bottom through which fuel is introduced and the burned lime removed.

Continuous Kilns. In the vertical kiln with mixed feed, the fuel and the limestone are charged in alternate layers, the lime being removed at the bottom while fresh fuel and limestone are charged in at the top.

Vertical kilns with separate feed are so designed that the fuel and limestone do not come in contact, the fuel being burned in separate fireplaces either set in the wall of the kiln or outside the kiln shell. The limestone therefore comes in contact only with the hot gaseous products of combustion.

Rotary Kilns. Rotary kilns have been applied to the calcination of lime to a limited extent. They are subject to the disadvantage of requiring that the stone be finely crushed prior to the calcination, and the product is consequently so finely divided that it is not marketable as lump lime, but can be sold only after grinding or hydrating, as either ground or hydrated lime.

The fuels for lime burning are wood, bituminous coal, and producer gas. Wood fuel possesses a distinct advantage over coal because of its longer flames and consequent better heat distribution throughout the mass of stone. The use of producer gas as a fuel for lime burning is confined to the larger and more modern plants.

A lime kiln in operation always contains three classes of material: (*a*) Stone undergoing preliminary heating through the agency of the escaping hot products of combustion; (*b*) stone undergoing dissociation through the agency of the direct heat of the fuel; (*c*) calcined lime which accumulates in the lower portion of the kiln and is withdrawn in part from time to time. The total amount of lime present in the kiln cannot be drawn at one time, because, aside from the desirability of letting it cool in the kiln itself, enough must remain at all times to fill the "cooler" (that portion of the kiln below the level of the fuel grate), thus preventing unburned stone from sinking below the level of the zone in which it is subjected to the action of the flames of the fires.

The operation of drawing consists in opening a draw-door provided in the lower part of the cooler, poking the lime loose with a bar, and allowing it to fall into a barrow or car placed underneath.

309. Treatment Subsequent to Calcination. Lime drawn cold from the kiln is immediately ready to be marketed as lump lime. When the kiln is not provided with a cooler it is necessary to spread the lime on a cooling floor or leave it standing in fireproof containers for a few hours before taking it to storage, packing house, or cars. Underburned and overburned material is easily recognized by its appearance, and is sorted out while being drawn into the barrows, or while it lies on the cooling floor.

PROPERTIES AND USES OF QUICKLIMES

310. Classification of Limes. Limes may be conveniently classified according to the purposes for which they are used, as agricultural limes, chemical limes, building limes, and finishing limes.

For agricultural limes, only the chemical composition is of importance; for limes used in the chemical industries, the chemical composition and the rate of hydration are important; building limes must be satisfactory as regards sand-carrying capacity, yield of lime paste per unit weight of lime, and strength; and finishing limes must be satisfactory with respect to rate of hydration, plasticity, sand-carrying capacity, color, yield, waste, hardness, time of setting, and shrinkage.

311. Chemical Composition. The approximate chemical composition of limes of various classes has been indicated in Art. 305, wherein limes were classified and graded according to their content of calcium oxide, magnesium oxide, and carbon dioxide. Table XXXI illustrates the range of composition found for quicklimes coming from different parts of the United States.

TABLE XXXI

ANALYSES OF QUICKLIMES

Class of Lime	High-calcium Quicklimes			Calcium and Magnesian Quicklimes			Dolomitic Quicklimes		
Component	Min. per cent	Max. per cent	Ave. of (10) per cent	Min. per cent	Max. per cent	Ave. of (6) per cent	Min. per cent	Max. per cent	Ave. of (2) per cent
SiO_2	0.33	2.20	0.81	0.66	9.00[1]	3.12	0.14	1.59	0.87
Fe_2O_3	0.08	0.43	0.23	0.17	0.59	0.41	0.19	0.39	0.29
Al_2O_3	0.02	0.42	0.22	0.18	2.57[1]	0.93	0.14	0.49	0.52
CaO	91.37	98.08	94.98	78.59	84.81	81.42	55.80	64.45	60.13
MgO	0.17	4.55	1.39	1.03	16.83	9.26	31.61	40.62	36.12
H_2O	0.36	3.45	1.66	0.63	12.42[2]	4.18	0.55	1.56	1.06
CO_2	0.20	1.84	0.83	0.24	1.94	0.18	0.35	3.01	1.68

[1] Excessively high in acid impurities. [2] Incipient air-slaking shows.

312. Hydration or Slaking. Quicklime intended for use in mortars for masonry construction, or as a wall plaster, must first be prepared for mixing with water to form a lime paste, by being slaked. The hydration or slaking of quicklime consists in the addition of sufficient water for the formation of calcium hydroxide, the operation being represented by the formula:

$$CaO + H_2O = Ca(OH)_2$$

$$75.7 + 24.3 = 100 \text{ (parts by weight)}$$

If the quicklime were absolutely free from impurities the amount of water required for complete slaking would equal 32.1 per cent by weight of the quicklime, but the fact that the quicklime is always more or less impure makes the amount of water actually required less than this. The formation of lime hydrate is attended by the evolution of considerable heat and an expansion to about 2½ or 3 times its former volume. Magnesian quicklimes, and particularly dolomitic quicklimes, slake more slowly than high-calcium limes, and the slaking is attended with the evolution of much less heat and far less expansion.

Lime intended for use in mortar is usually slaked in a mortar mixing box, the mixture being stirred until a thin paste, or "putty," has been formed. The putty is then covered with sand to protect it from the action of the air. Lime paste, or putty, designed for use as a plaster should be allowed to season for several weeks.

The reaction involved in the hydration of quicklime may result in the production of either crystalline or colloidal calcium hydroxide, the relative quantity of one or the other being dependent upon the conditions maintained during the reaction. Crystals of calcium hydroxide form and grow slowly, whereas the colloidal hydroxide forms with great rapidity. Consequently, the more rapid the reaction the greater the proportion of colloidal hydroxide. The reaction may be most readily hastened by using warm water in slaking. The percentages of colloidal hydroxide may also be increased by violently agitating the material during the reaction. A preponderance of colloidal hydroxide is desirable from the standpoint of the mason, who judges a mortar by its plasticity, yield, and sand-carrying capacity.

The hydration of high-calcium quicklimes is attended with danger of "burning," due to too great a rise in temperature. "Burned lime" appears to be chemically inert and is useless in a mortar or plaster. Burning may best be avoided by securing an intimate contact between every particle of lime and the water. Great watchfulness and continuous stirring of the mixture are therefore necessary.

No danger of burning attends the slaking of most magnesian quicklimes, or of any dolomitic quicklime. On the contrary, the danger here is that the quicklime may never be properly slaked before being used.

"Air-slaked" lime is a very different thing from the ordinary slaked lime. Quicklime exposed to the air absorbs moisture and becomes slaked lime, the expansion accompanying hydration causing the lumps to fall into a more or less fine powder. Immediately, the slaked lime is attacked by the carbon dioxide of the air, and the resulting product is simply powdered calcium carbonate, $CaCO_3$. The term "air-slaked" will be seen to be a very misleading one, for the quicklime has not only been slaked by the moisture in the air, but further has been ruined completely as a cementing material by taking up carbon dioxide while in a loose powdered state. The fact that quicklime does "air-slake" when exposed to the air is not an unmitigated evil, however, because it renders possible the storage and even the shipment of ground lime without its being contained in tight bags or barrels. The quicklime at the surface becomes "air-slaked," but by so doing it immediately forms a film which protects the bulk of the material.

The rates of hydration of various quicklimes are dependent, first, upon the physical condition of the material, finely divided or porous quicklimes being more quickly hydrated because of their greater accessibility to water; second, upon the chemical composition of the quicklimes, high-calcium quicklimes being more quickly hydrated than magnesian or dolomitic quicklimes, and pure limes of either class being more quickly hydrated than impure ones; third, upon the temperature of burning of the quicklime, any underburned quicklime having little ability to hydrate, and overburned limes behaving similarly owing to the influence of impurities.

A little supervision over the operation of slaking will pay for itself by insuring the production of the greatest possible quantity of suitable putty. To find out how to slake a new lot of lime, two or three handfuls should be placed in a bucket and barely covered with water of the same temperature as that to be used in the field. Any crumbling of the lumps denotes slaking, and the time before slaking should be carefully noted. If the slaking begins in less than 5 minutes the lime is quick-slaking; from 5 to 30 minutes, medium-slaking; more than 30 minutes, slow-slaking.

Quick-slaking lime should always be added to the water, not the water to the lime. Enough water should be present to cover the lime completely, and an additional supply should be available for immediate use. The mixture should be watched carefully, and at the slightest appearance of escaping steam it should be hoed thoroughly and enough water added to stop the steaming.

For medium-slaking lime, enough water should be added to the lime to half submerge it. Immediate hoeing should follow the appearance of any steam, and small amounts of water should be added when necessary to prevent the putty from becoming dry and crumbly.

For slow-slaking lime, only enough water should be added to the lime to moisten it thoroughly, and it should then be allowed to stand until the reaction has started. Small amounts of water should then be added, care being taken not to cool the mass, and there should be no hoeing until the slaking is practically complete. The slaking mass must be kept warm. In cold weather, hot water should be used if available, and the mortar box should be covered.

313. Plasticity, Sand-carrying Capacity, and Yield. The term "plasticity" is commonly used to describe the spreading quality of the material in plastering. If it spreads easily and smoothly, it is plastic; if it sticks or drags under the trowel, or cracks, curls up, and drops behind the trowel, it is non-plastic, or "short." Magnesian limes produce mortars that work smoothly under the trowel; high-calcium mortars are likely to be sticky and work short.

Practically all lime used structurally is made up in the form of a mortar by the addition of sand to lime paste. This circumstance is due not simply to the fact that sand is cheaper than lime, but also to the fact that the great shrinkage which accompanies the setting and hardening of lime putty can thus be diminished and the consequent cracking be prevented. The extreme stickiness of some high-calcium limes is also counteracted by the sand.

It is necessary to mix the lime with 2 to 4 parts of sand to 1 of lime putty, and it becomes highly important that the "sand-carrying capacity" of the lime be properly established. If too little sand is used, excessive shrinkage will cause a weakening of bond between the plaster or mortar and the masonry materials or plastered surface. On the other hand, too much sand produces a non-plastic and weak mortar.

The sand-carrying capacity of a lime is expressed by the number of parts of sand which may be added to the lime without rendering the mortar too stiff to work well under the trowel. No fixed standard of sand-carrying capacity has been established. Common experience has shown, however, that pure high-calcium limes excel in sand-carrying capacity, magnesian limes carry less sand, and dolomitic limes carry least of all.

The volume of paste of a definite consistency which a given amount of lime will yield when slaked is a matter of great practical importance. This "yield" of a lime can be expressed by the volume of paste of an arbitrary consistency produced per unit weight of dry quicklime. The consistency chosen is usually such that a 2-inch cylinder of putty 4 inches high will settle to a height of 3½ inches upon removal of the mold. Pure high-calcium limes yield the largest volume of paste per unit of weight; impure high-calcium and magnesian limes expand less upon being slaked and therefore show a lower yield; and dolomitic limes produce the smallest volume of paste of any class of quicklime.

Usually, between 25 and 30 pounds of quicklime will produce 1 cubic foot of putty. On this basis, the yield will be 0.033 to 0.040 cubic foot of putty per pound of quicklime.

314. Waste. The determination of the proportion of a 5-pound sample of quicklime made into a paste, that, after standing 24 hours, cannot be washed through a 20-mesh sieve by a gentle stream of water, serves as a check upon the proper carrying out of the various steps in the manufacturing process.

The material that cannot be washed through the sieve consists of lumps of foreign matter which did not disintegrate when the lime was slaked. These lumps impair the working qualities of plaster, and, if they consist of overburned lime, they are likely to become hydrated and expand after the plaster sets, thus causing the "popping" or "pitting" which not infrequently disfigures the surface of plastered walls.

315. Hardness, Time of Setting, and Shrinkage. The hardness of lime mortar, meaning by the term "hardness" resistance to impact and abrasion, has an important bearing upon the suitability of the material for use in wall plasters. No method of testing the hardness of lime mortars has been standardized. Comparative tests made upon various classes of limes, as well as the common experience of builders, have shown, however, that dolomitic limes produce the hardest mortars, magnesian limes are less hard, and high-calcium limes least hard.

The setting of lime and lime mortar is a chemical process involving essentially only the evaporation of the large excess of water used in forming the lime paste, followed by the gradual replacement of the water of the hydroxide by carbon dioxide in the atmosphere, causing the lime hydrate to revert to the original calcium carbonate. Dry carbon dioxide will not react with dry hydrated lime, and it is therefore necessary that excess moisture be present.

The time of setting of limes and mortars is important in connection with the use of the material in plastering operations. Lime is naturally slow-setting, a circumstance which causes the loss of considerable time between the application of the different coats. The slow-setting properties of lime, as much as any other one characteristic, have been responsible for the increasing use of quick-setting gypsum plasters.

The humidity and the amount of CO_2 in the atmosphere influence the rate of setting of lime, drying the air and charging it with carbon dioxide, greatly accelerating the setting process.

No experimental method of determining the setting has been standardized. It is a fact well understood by practical masons, however, that magnesian limes are slower-setting than high-calcium limes, and the dolomitic limes set still more slowly.

The decrease in volume, or shrinkage, of lime putty, which accompanies the process of setting and hardening, is directly explained by the volume of water lost, the net decrease in volume being slightly affected by an expansion entailed by the gain in carbon dioxide. It is the universal practice to reduce the contraction and consequent cracking of mortars and plasters by the addition of several parts of sand to one of lime paste. The only exception to this rule is that neat lime putty is sometimes spread as a thin "skim" coat on plastered walls. In this coating, fine hair-cracks do occur, but they penetrate to so slight a depth that they do not open up appreciably.

The amount of shrinkage shown by limes is not closely related to chemical composition, but all magnesian and dolomitic limes shrink less than high-calcium limes.

316. Tensile and Compressive Strength of Lime Mortars. The physical properties of lime mortar vary with the chemical composition of the lime, the amount and character of the sand, the amount of water, and the conditions under which the mortar sets. The very wide variation in the data obtained from tests makes it impossible to present definite statements with regard to either the tensile or compressive strength.

Magnesian limes make stronger mortar than calcium limes, as shown in Fig. 96, and comparatively fine sand makes stronger mortar than coarse sand.

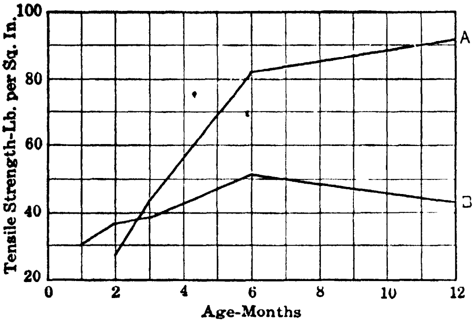

FIG. 96.—Tensile Strength of Lime Mortars (1 : 2).

A, Magnesian Lime.
B, High-calcium Lime.

317. Specifications. The American Society for Testing Materials has adopted the specifications for chemical composition of limes given in Table XXXII.

TABLE XXXII

A.S.T.M. SPECIFICATIONS FOR LIMES

Composition	Calcium Lime	Magnesian Lime
Calcium oxide, minimum, per cent	75	..
Magnesium oxide, minimum, per cent	..	20
Calcium and magnesium oxides, minimum, per cent	95	95
Silica, alumina, and oxide of iron, maximum, per cent	5	5
Carbon dioxide, maximum, per cent		
(*a*) If sample is taken at kiln	3	3
(*b*) If sample is taken at any other place	10	10

HYDRATED LIME

318. Process of Manufacture. Hydrated lime is a dry, flocculent powder resulting from the hydration, at the place of manufacture, of ordinary quicklime. Three stages of manufacture characterize the preparation of hydrated lime.

> The lump quicklime is crushed to a fairly small size.
>
> The crushed material is thoroughly mixed with a sufficient quantity of water.
>
> The slaked lime is, by air separation, screening, or otherwise, separated from lumps of unhydrated lime and impurities, or the entire mass must be finely pulverized.

The degree of crushing practiced at various hydrated lime plants varies greatly. In some plants the quicklime is crushed to a 1-inch size; in others, to a size of ½ inch or under. A few plants, after crushing the quicklime, pulverize it so that the greater portion will pass a 50-mesh sieve.

The two methods extensively used for hydrating quicklime are the "batch" process and the continuous process.

The "batch" process hydrator consists of a revolving pan provided with plows, arranged in a horizontal spiral, which stir up and mix with lime the water which is added in the form of spray. The hydrated lime is scraped from the pan through an opening in the center into a hopper below the hydrator.

The "continuous" process hydrator consists of a number of cylinders, arranged one above the other, which are provided with screw conveyors. The quicklime is fed into the upper cylinder in a continuous stream, and here water is sprayed upon it, the amount being regulated by valves. The moist lime is gradually worked by the conveyors through the upper cylinder into the lower ones, and by the time it is discharged from the lowest cylinder it is entirely hydrated.

Any impurities in the lime will not slake, and any imperfectly hydrated lime can be removed from the finished product by screening or air separation.

The form of screen usually employed consists of a wire netting stretched on an inclined frame which is mechanically agitated as the material traverses its length. The usual size is from 35 to 50 meshes per linear inch. The whole structure must be enclosed to keep in the dust.

Air separation systems usually involve the use of a Raymond impact mill or similar device in which the hydrate is subjected to the beating action of rapidly revolving blades. A current of air carries off the fine material in suspension, while the larger particles settle out. The fine material is subsequently deposited in a chamber provided for the purpose in the air duct, the precipitation being effected by the reduction in velocity of the air current. The air circuit is a closed one, the same air being circulated over again, and it is therefore a dust-proof device. The size of the particles is easily regulated by varying the velocity of the air current.

319. Properties and Uses. Hydrated lime and ordinary lime that has been properly slaked on the work are the same material, and therefore should have identical physical properties. Experience has shown, however, that stronger and more quickly setting mortars, which shrink less upon setting and hardening, are derived from hydrated limes than from ordinary quicklime. On the other hand, mortars prepared from hydrates are generally inferior to those prepared from quicklimes from the standpoint of plasticity, sand-carrying capacity, and yield, unless the hydrated lime paste is allowed a period of seasoning before being used. Hydrates are being constantly improved in this respect.

The strength of hydrated lime mortars, both in tension and in compression, is somewhat higher than that of the corresponding quicklime mortars. This superiority is particularly noticeable in the high-calcium limes.

320. Tests. The principal physical tests for hydrated lime that have been standardized are fineness and constancy of volume. Brief extracts from the American Society for Testing Materials Standards follow:

Fineness. "The fineness shall be determined as follows: 100 grams of the sample as received shall be placed on a No. 30 sieve which shall be nested above a No. 200 sieve. The material shall be washed by means of a stream of water from a faucet. The washing shall be continued until the water coming through the sieve is clear, but in no case should the washing be continued for more than 30 minutes. The 100-gram sample shall leave, by weight, a residue of not more than 0.5 per cent on a No. 30 sieve, and not more than 15 per cent on a No. 200 sieve."

Constancy of Volume. Twenty grams of the sample and 100 grams of standard Ottawa [*] sand shall be mixed with enough water to give a plastic mortar of rather dry consistency. This shall be spread on a glass plate to form a layer ¼ inch thick by 4 inches square. The pat formed shall be aged 24 hours in air and then be soaked in water until a film of water will stand unabsorbed on its surface.

A thick cream composed of 20 grams of the sample and sufficient water shall then be spread on the surface of this pat and the whole aged for 24 hours in air. It shall then be subjected to steam above boiling water in a closed vessel for 5 hours, and after cooling it shall show no popping, checking, warping, or disintegration.

Consistency and Plasticity. When standard consistency is required, a modified "Vicat needle" is used.[†] Plasticity is determined by the testing of a paste of standard consistency with an "Emley plasticimeter."

321. Hydrated Lime vs. Quicklime. The superiority of hydrated lime over the ordinary lump lime, from the standpoint of the mortar

[*] See Art. 380.

[†] See Art. 378.

strength developed, has been indicated. The advantage accruing from the use of a material that need only be mixed with water, instead of being slaked upon the work with the attendant danger of burning or incomplete hydration, has also been noted. There remain certain advantages and disadvantages to be derived from the use of the commercial hydrate, and these will be considered briefly.

Hydrated lime can be more conveniently handled than lump lime because of its powdered condition, and can safely be stored or shipped by rail or water in cloth or paper bags or even in bulk. On the other hand, lump lime deteriorates rapidly in storage or transportation because of air-slaking, is considered an unsafe commodity to carry by water, and wherever kept always constitutes a fire hazard.

One property of hydrated lime which often constitutes an advantage on construction work is the fact that it is ready to be immediately incorporated with sand and water to form mortar, whereas ordinary lime must be allowed to season after being slaked, thus causing delay.

The fact that hydrated lime is a physically dry material is an advantage in mixing mortars. The dry hydrate can be mixed with sand much more easily than a lime paste or putty, and a more homogeneous mixture is obtained before the excess water is added to make a plastic mortar.

On the other hand, mortars prepared from hydrated lime are very "short" and non-plastic, the volume of lime paste derived is small, as compared with that obtainable from quicklimes, and the sand-carrying capacity is low. The lack of plasticity of hydrated lime mortars is alone sufficient to condemn the material from the standpoint of the practical mason and plasterer. Some hydrates are so lacking in colloidal properties that they are actually gritty.

A large amount of hydrated lime is utilized in Portland cement mortars and concretes; it is also used in combination with gypsum plaster.

In certain localities a service is maintained whereby prepared plasters and mortars are available to the consumer for immediate use. The advantages of such a service with respect to uniformity and quality of product are obvious. An additional feature is the highly plastic condition of the product obtained by a mechanical agitating or "whipping" process to which the slaked lime is subjected.

QUESTIONS

1. Distinguish between quicklime and hydrated lime.
2. Describe the essential steps in the manufacture of quicklime.
3. Write the chemical equation representing the manufacture of a high-calcium quicklime.
4. Write the chemical formula representing slaking of quicklime.
5. Describe proper methods of slaking quicklime. What is "burned lime"?

6. What is "air-slaked" lime?

7. Describe the chemical changes that take place in the hardening of lime mortar. Compare with the hardening of gypsum plaster.

8. Can lime mortar be used under water?

9. A plasterer buys quicklime from an unfamiliar source. Describe some simple tests that he might perform to test its quality.

10. What is the purpose of adding sand to lime paste?

11. State the three stages of preparing hydrated lime from quicklime.

12. A plasterer needs a smooth mortar that trowels well. Would commercial hydrated lime meet this requirement? Give reasons for your opinion.

13. What are the advantages of hydrated lime as compared with quicklime?

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CHAPTER XV

CEMENTS

322. Introductory. Gypsum plaster and lime are cementing materials which are comparatively simple both in composition and in chemical action. Cements, however, comprise a class of products of very complex and somewhat variable composition and constitution, whose physical characteristics are not definitely fixed, and whose actual constitution is imperfectly understood.

Cements all possess, in common, one property known as *hydraulicity*, i.e., the ability to set and harden under water. In composition they agree to the extent that they all consist essentially of lime, silica, and alumina, or of lime and magnesia, silica, and alumina and iron oxide. The hydraulic cements include hydraulic limes, grappier cements, puzzolan * cements, slag cements, natural cements, Portland cements, Portland-puzzolan cements, and alumina cements.

HYDRAULIC LIMES

323. Definition and Classification. The hydraulic limes include all those cementing materials made by burning siliceous or argillaceous limestones, whose clinker after calcination contains a sufficient percentage of lime silicate to give hydraulic properties to the product, but which at the same time contain normally so much free lime that the mass of clinker will slake on the addition of water.

The hydraulic limes, therefore, occupy an intermediate position between the common limes and the more complex cements.

324. Hydraulic Limestone. The ideal hydraulic limestone rock should have such a composition that, after all the silica has combined with lime during calcination, sufficient free lime remains to disintegrate the kiln product by the expansive force set up when it is slaked.

The limestones used in the manufacture of hydraulic limes usually contain from 40 to 50 per cent of lime and magnesia, 4 to 17 per cent of silica, and usually not more than 4 per cent of alumina and iron oxide.

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* The term "puzzolan," which is commonly applied to this class of cements by American authorities, is a corruption of the name "puzzuolana" which refers to the class of volcanic materials first utilized as hydraulic cementing material at the town of Puzzuoli, near Naples. Continental writers call them "puzzuolana" cements.

325. Calcination. Hydraulic limes are burned in continuous kilns. The operations involved in the process of calcination are practically the same as for common lime except that the temperature required is somewhat higher.

326. Slaking and Subsequent Treatment. The theory of slaking of hydraulic lime differs from the slaking of common quicklime in no respect except that in the former case the quicklime, which will slake, is intimately associated in lumps with lime silicate, underburned limestone, and some aluminates and ferrites, none of which can be slaked. The expansion of the quicklime in slaking breaks up the entire mass into a fine powder which will consist principally of lime silicate together with one-fourth to one-third as much hydrated lime.

Hydraulic lime is slaked at the place of manufacture. The lump lime as drawn from the kiln is spread out in thin layers and sprinkled lightly with water. It is then shoveled into heaps or bins where it is allowed to remain for about 10 days till the slaking is completed. In order that the product may be a fine, dry powder, the amount of water must be exactly right.

327. Uses. In spite of their designation, hydraulic limes are not suitable for subaqueous construction. They are too slow-setting to render their use on general construction work practical, and their comparative weakness makes competition with natural and Portland cement impossible. Their only present value is as an architectural decorative material rather than a material for engineering construction.

328. Grappier Cement. In slaking hydraulic lime, a certain proportion of the kiln product either does not contain sufficient lime or is not sufficiently burned to be slaked upon the addition of water, and consequently remains as hard lumps called "grappiers." The slaked material is passed over screens of about 50 meshes per linear inch, which reject all the larger particles. This rejected material is valuable or not according to whether it consists principally of lumps of lime silicate on the one hand or unburned limestone on the other. As a rule, all the grappiers are finely ground under millstones and a certain proportion is added to the lime, thereby increasing its hydraulicity in proportion to the amount of lime silicate present. The ground grappiers are also separately marketed as a special cement known as "grappier cement."

PUZZOLAN CEMENTS

329. General. The oldest known hydraulic mortars were undoubtedly made by the incorporation of a volcanic tufa with slaked lime and sand. Thus were produced the cements extensively used by the Romans and other ancient peoples in the construction of many engineering structures, a few of which remain today in a remarkable state of preservation.

The activity of the volcanic material depends upon the presence of weakly acid silicoaluminates which combine more or less readily with lime hydrate at atmospheric temperatures.

330. Definition of Puzzolans and Puzzolan Cement. The natural or artificial materials that contain a sufficiently large percentage of available silica to combine with lime hydrate and form a cement possessing hydraulic properties are known as "puzzolans."

Puzzolan cements include all that class of hydraulic cementing materials which are made by the incorporation of natural or artificial puzzolans with hydrated lime without subsequent calcination.

The true puzzolan cement, often called "slag cement," made by incorporating blast-furnace slag with hydrated lime without subsequent burning, must not be confused with the Portland cement, which is made by finely pulverizing the clinker derived by the calcination of an intimate mixture of the same materials.

331. Natural Puzzolanic Materials. Natural puzzolanic materials of commercial importance as cement materials are usually direct products of volcanic action and are generally derived from deposits of more or less agglomerated volcanic ash. Typical examples of these puzzolanic materials are puzzuolana, trass, santorin, and tuff, or tufa.

The natural puzzolanic materials and the principal artificial puzzolanic material, granulated blast-furnace slag, have their origin in practically the same processes. In both, more or less finely divided siliceous material is derived by the sudden cooling and ejection into air or immersion in water of a fused silicoaluminous substance. Diatomaceous earth is sometimes used as a puzzolanic material.

332. Manufacture of Puzzolan Cements. The preparation of puzzolan cements is a simple mechanical process involving nothing more than the screening, mixing, and grinding of the two constituents.

Most deposits of natural puzzolans are subject to great variation in the quality of the material, therefore necessitating careful selection or sorting of the quarry product to exclude inferior material. Screening of the puzzolan is usually necessary in order to exclude undesirable adulterants.

Puzzolanic rock is not usually mixed with hydrated lime at the place of manufacture, but is pulverized and marketed as a material to be incorporated with hydrated lime paste and sand upon the site of the construction work. The proportions of the mixtures used in mortars are not fixed, but the proportion of lime usually amounts to one-third to one-half the proportion of puzzolan, and the puzzolan cement thus formed may be combined with sand up to about three times the proportion of cement.

333. Properties and Uses. Puzzolan cements made from natural materials hold an unimportant place among structural materials.

SLAG CEMENTS

334. Definition. Slag cement may be defined as an intimate mechanical mixture of granulated blast-furnace slag of suitable chemical composition, with hydrated lime, the materials having been finely pulverized before, during, or after mixing.

The mixture is not calcined, and the product is not to be confused with the true Portland cement which is produced by the calcination and subsequent pulverization of a properly proportioned mixture of blast-furnace slag and raw limestone.

335. Blast-furnace Slag. Blast-furnace slags, such as are suitable for use in slag cements, are fusible lime silicates derived as waste products from the operation of blast furnaces in smelting iron from its ores. The slag is formed for the most part by the combination in the furnace of the earthy part of the ore, with lime from limestone which is charged with the ore as a flux. Slags are produced in many metallurgical processes other than the reduction of iron ores. Only the latter process, however, is capable of producing the very basic slag required for cement manufacture.

The required composition of the slag according to American practice is within the following approximate limits: CaO, 48 to 50 per cent; SiO_2, 32 to 35 per cent; Al_2O_3, 12 to 16 per cent; MgO, Fe_2O_3, etc., 2 to 5 per cent.

Slag as it comes from the blast furnace, if allowed to cool slowly, is a very dense and hard material, and has such a chemical constitution that even when pulverized it does not combine energetically with water, nor exhibit more than very feebly hydraulic properties. If the molten slag is cooled very rapidly, however, by means of cold water, it becomes broken up into small porous particles which can be economically handled by the pulverizing machinery.

Two important chemical effects are also attained by the process of granulating the slag; the slag is rendered more hydraulic, thus providing a stronger cement; and the content of undesirable sulfides always encountered in slags is reduced.

336. Manufacture of Slag Cements. The process of manufacture of slag cements involves the following operations: granulation of the slag, drying the slag sand, preparation of the hydrated lime, proportioning the mixture, mixing, and grinding.

The slag may be granulated by a jet of high-pressure steam which the stream of slag encounters as it issues from the furnace. Air jets have also been similarly used, but both these methods have been generally replaced by an arrangement whereby the stream of slag from the furnace falls into a trough containing a rapidly flowing stream of cold water. This method is a very satisfactory one as it produces a slag sand which is quite porous and friable and has the proper chemical composition. It is charged with much moisture, however, and must be dried before being mixed with the hydrated lime.

The slag as it comes from the bins, into which it has been discharged by the granulating device, carries from 15 to 45 per cent of water. This water is removed through the agency of heat in either a rotary cylinder or in a vertical shaft dryer, into which the material is introduced at the top and dried by ascending hot furnace gases as it traverses a series of inclined baffle plates toward the base.

The hydrated lime used in slag cement in American practice is a very pure high-calcium lime.

The standard proportions of slag and lime vary at different plants from as low as 25 pounds to as high as 45 pounds of lime for 100 pounds of slag sand.

The best method of grinding and mixing the slag and lime probably consists in grinding the slag sand in a ball mill or other type of grinder, adding the hydrated lime, and mixing and pulverizing the mixture simultaneously in a tube mill or other type of cement-finishing mill.

Slag cements are normally more slow-setting than Portland cements, and on this account are often treated with some class of puzzolanic material which will hasten the setting. Materials so used are burned clay, high-alumina slags, certain active forms of silica, and, in the patented "Whiting" process, caustic soda, sodium chloride, or potash. The amount of such materials added as an accelerator does not usually exceed about 3 per cent by weight, and unless the material is to qualify under the usual specifications for Portland cement no accelerator should be necessary. Any addition to the cement made for the purpose of regulating the set must be made prior to final pulverization.

337. Properties and Uses of Slag Cements. The specific gravity of slag cements usually ranges between 2.7 and 2.85. This fact affords a means of distinguishing slag cements from natural cements, which rarely fall below 2.9, and Portland cements, which under the standard specifications must be not less than 3.1.

The fineness of grinding practiced in making slag cements is about equal to that commonly attained in grinding Portland cements.

The use of slag cement is limited to unimportant structures or to work requiring large masses of concrete masonry where weight and bulk are more important than great strength. It is seldom used on structures above the foundations, and never on comparatively light reinforced-concrete construction.

NATURAL CEMENTS

338. Definition. Natural cement may be defined as the finely pulverized product resulting from the calcination of a natural argillaceous limestone at a temperature sufficient to drive off the carbon dioxide gas and also decompose the clay and effect the formation of aluminates, ferrites, and silicates.

The distinctions between natural and Portland cements may be summarized as follows:

	Natural Cements	Portland Cement
Raw material	Natural argillocalcareous rock	Artificial argillocalcareous mixture
Calcination temperature	Low	Relatively high
Chemical composition	Variable, not under control	Controllable within narrow limits
Color	Usually yellow to brown	Usually blue-gray
Specific gravity	2.7 to 3.1	3.1 to 3.2
Rate of setting	Normally rapid	Relatively slow
Strength	Low	Relatively high

339. Natural Cement Rocks. Natural cements are invariably made by the calcination of a natural clayey limestone carrying from 13 to 35 per cent of clayey material, 10 to 20 per cent of which is silica and the balance alumina and iron oxide. The hydraulic properties of the cement are entirely due to the presence of this clayey material. The calcium carbonate of the limestone may be replaced to a considerable degree by magnesium carbonate, resulting in the replacement of lime by magnesia to a corresponding degree in the manufactured product.

Argillaceous limestones of the composition required for the manufacture of natural cement are widely distributed. In only comparatively few districts, however, has the natural cement industry become commercially successful. This fact is due to the necessity for certain commercial advantages dependent upon the character and location of the quarries. Among these requisites may be mentioned a rock of fairly uniform composition, a favorable location of the rock beds for cheap extraction of the cement rock, cheap fuel, and good transportation facilities.

340. Calcination. The rock as it is charged into the kiln consists essentially of lime and magnesium carbonate with a more or less definite percentage of clayey matter. The chemical changes that take place during calcination may be briefly mentioned as follows:

Water mechanically held by the rock is first driven off; at a temperature of about 800° C. (1472° F.) magnesium carbonate is dissociated, the carbon dioxide being driven off; at a temperature of about 900° C.

(1652° F.) the lime carbonate is similarly dissociated; at a temperature of 900° C. (1652° F.) to 1000° C. (1832° F.) the clay is decomposed and aluminates and ferrites of lime and magnesia are formed; lastly, at a temperature of about 1300° C. (2372° F.), silicates of lime and magnesia are formed.

The most common type of kiln in the natural cement industry in the United States is of the continuous vertical mixed-feed type, the rock and fuel being either mixed or charged in alternate layers. The usual fuel for natural cement burning is bituminous coal.

341. The Clinker. The output of a natural-cement kiln includes three classes of material: hard-burned clinker; soft, porous, moderately burned material; and practically unburned material. With some rocks the best cement is derived from the soft, moderately burned material; with others, the best results are obtained from a mixture of the first two classes. Unburned material is valueless.

With cement rock high in lime and magnesia, the possible range of temperature for proper calcination is shortened, with consequent greater possibility of high percentages of free lime. The presence of this free lime may be neutralized by some method of slaking. This is commonly done by sprinkling or steaming the unground clinker. This expedient decreases grinding costs, since the slaking of the lime disintegrates the clinker to some extent.

The clinker is crushed in some form of crusher and then finished in some one of the various types of grinders and pulverizers used in Portland cement manufacture.

342. Properties of Natural Cement. *Chemical Composition.* The average composition of various natural cements is indicated by the following summary:

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO
22.3–29.0%	5.2–8.8%	1.4–3.2%	31.0–57.6%	1.4–21.5%

It will be apparent that the composition of natural cements is extremely variable. The wide variations in composition are accompanied by great differences in mechanical properties.

Specific Gravity. The specific gravity of natural cements is slightly below that of Portland cements, the average being about 2.95.

Time of Setting. Natural cements normally are quick-setting as compared with Portland cement. The standard specifications prescribe that the initial set shall take place in not less than 10 minutes, and hard set in not less than 30 minutes or more than 3 hours as determined by the Vicat needle.

The addition of gypsum or plaster of Paris has a very marked effect in retarding the set of natural cements, the degree of retardation with a given percentage of gypsum being largely dependent upon the chemical composition of the particular cement.

Fineness. The general practice is to meet and even exceed the requirements of the standard specifications of the American Society for Testing Materials, which permit a maximum residue of 30 per cent on the 200-mesh sieve and 10 per cent on the 100-mesh sieve.

Tensile Strength. In tensile strength, natural cements vary quite as much as they do in other physical properties. This variation is found not only in comparing cements from different localities, but even in comparing samples taken at different times from the output of any one locality. The only general statement that may be made concerning their strength is that natural cements rarely show more than half the tensile strength of Portland cement of the same age. This is true not only of neat cement, but also of mortars of all proportions.

The standard specifications of the American Society for Testing Materials fix the following minimum requirements for tensile strength:

	Neat Cement, lb. per sq. in.	1 : 3 Standard Mortar, lb. per sq. in.
24 hr. in moist air	75	...
24 hr. in moist air, 6 days in water	150	50
24 hr. in moist air, 27 days in water	250	125

It is further stipulated that the cement shall show no retrogression in strength within the periods specified.

Compressive Strength. The above remarks concerning the variability of tensile strength of natural cements apply equally well to compressive strength. In general it may be stated that the compressive strength of natural cement, neat or mortars, rarely exceeds one-third that of Portland cement in similar mixtures.

343. Uses of Natural Cement. When economy is effected thereby, natural cement may be substituted for Portland cement in mortars and concrete for dry, heavy foundations where the stresses encountered will never be high, for backing or filling in massive masonry in dry situations where weight and mass are more essential than strength. It should not be used in exposed situations, should not be placed under water, and is unsuitable for marine construction.

PORTLAND CEMENT

344. Historical. In 1824, Joseph Aspdin, a brick mason of Leeds, England, was granted a patent on a method of manufacture of a cement for which he proposed the name *Portland cement,* because of a real or fancied resemblance of the concrete made with it to the natural limestone extensively quarried for building purposes at Portland, England.

Portland cement was manufactured first in the United States near Kalamazoo, Mich., in 1872. At Coplay, Pa., in 1875, Portland cement was made by David O. Saylor, by calcining at a high temperature a mixture of argillaceous limestone rock with a comparatively pure limestone.

345. Definition. The term Portland cement is defined by the American Society for Testing Materials as follows:

> Portland cement is the product obtained by pulverizing clinker consisting essentially of calcium silicates, to which no additions have been made subsequent to calcination other than water and/or untreated calcium sulfate except that additions not to exceed 1 per cent of other materials may be added, provided such materials have been shown not to be harmful by tests prescribed and carried out by Committee C-1 on Cement.

There is a further requirement that the magnesia (MgO) must not exceed 5 per cent and the sulfuric anhydride (SO_3) must not exceed 2 per cent.

The approximate proportions for Portland cement are:

	PER CENT
Lime (CaO)	60–65
Silica (SiO_2)	20–25
Iron oxide and alumina (Fe_2O_3 and Al_2O_3)	7–12

The raw materials obtained from natural deposits must be mixed in exact proportions obtainable only in an artificial way under chemical control. Burning to an incipient fusion (sintering) insures the high density so essential to Portland cement. The presence of magnesia and sulfuric acid is unavoidable because both are contained in the raw materials and in the fuel. The percentage of each is therefore limited because an excess of either tends to cause unsoundness of cement.

346. Portland Cement as a Structural Material. Portland cement is by far the most important of all masonry materials in modern engineering construction and ranks second only to steel as a structural material. As monolithic concrete it is used in all types of masonry, such as foundations, footings, piers, abutments, dams, retaining walls, pavements, and roadways. When reinforced with steel it is used for framework, walls, floors, and roofs of buildings, for bridges, for tunnels, subways, conduits, and innumerable other purposes. In combination with sand and lime it serves as mortar for laying brick or stone, and as a plaster or stucco it is applied to either exterior or interior walls upon a base of terra cotta, brick, or metal lath.

One great difference exists in the conditions under which cement is used as compared with steel. Steel is delivered upon the work as a finished material, manufactured under standardized conditions, every step in the metallurgical processes involved in its production and the mechanical operations of its fabrication having been most carefully supervised. Upon the work the fabricated units are assembled by workmen specially trained in doing this one class of work.

Cement, on the other hand, although manufactured under well-standardized conditions, is received upon the work as one ingredient only of a structural material, which is built in place. The materials that are combined with it to form concrete or mortar, i.e., sand and crushed stone or gravel, are sometimes not carefully examined or selected, and the mixing and the deposition of the material in place often does not receive proper supervision.

One of the newer developments in concrete construction methods is ready-mixed concrete. This eliminates careless handling of the cement and other materials under job conditions and places the mixing under careful control in a centralized plant. This method of handling insures a more constant product than is generally possible under small job control and places the concrete in the list of other construction materials such as steel, brick, and wood, which are merchandised under rigid specifications.

RAW MATERIALS

347. General. The essential constituents of Portland cement are lime, silica, and alumina. With the exception of lime, these substances are found free in nature, but not, however, in a form suitable for use in cement manufacture. Lime is always used in the form of a carbonate, and silica and alumina in the form of clay, shale, or slate.

The following classification of the raw materials may be made:

Calcareous ($CaCO_3$ over 75%)	Argillocalcareous ($CaCO_3$ = 40–75%)	Argillaceous ($CaCO_3$ under 40%)
Pure limestone Pure chalk Pure marl	Clayey limestone Clayey chalk Clayey marl Blast-furnace slag	Slate Shale Clay

The combination of the materials in any two of these groups which will give a mixture of proper composition might be taken as the raw material for Portland cement. The only combinations which have been used to any extent in America are:

Limestone and shale or clay.
Pure limestone and argillaceous limestone (cement rock).
Marl or chalk and clay or shale.
Limestone and blast-furnace slag.

Although proper chemical composition and physical character are the primary requisites for the raw materials chosen, many other considerations assume great importance when the factors contributory to the economical manufacture of Portland cement are considered. Among these may be mentioned the availability of the deposits, the location with respect to a market, transportation facilities, and also fuel supplies.

348. Limestone. When pure, limestone forms the mineral calcite ($CaCO_3$), and all limestones consist essentially of calcium carbonate combined with more or less impurities consisting of magnesia, silica, iron, alkalies, and sulfur.

Carbonate of magnesia occurs very often in limestone, but much more than 5 per cent will make the limestone unsuitable for use.

Silica may be present either alone or in combination with alumina. When alone, silica does not combine with lime in the kiln, and more than a very small amount renders a limestone unfit for use. Silica combined with alumina, on the other hand, does readily combine with lime in the kiln. The argillaceous limestones are among the most important raw materials for the manufacture of Portland cement.

Iron occurs usually as either the oxide (Fe_2O_3) or sulfide (FeS_2), and less commonly as a carbonate or silicate. Except as a sulfide the iron forms a useful flux, aiding the combination of lime and silica in the kiln. As a sulfide it is injurious and to be avoided if in amounts over 2 to 3 per cent.

The alkalies, soda and potash, commonly occur in limestones in small percentages. Unless present in quantities above about 5 per cent, in which event they may be carried over into the cement with harmful results, they will be largely driven off in the kiln with no consequent effect upon the cement.

Sulfur may be present as iron pyrite or as lime sulfate. Either substance is extremely injurious and not more than 2 per cent can be tolerated.

The approximate range of composition of limestones used in American Portland cement manufacture is indicated by the following summary:

Component	Approximate Range, per cent	Usual Percentage
$CaCO_3$	88.0–98.0	93.0–97.0
SiO_2	0.3– 8.0	0.4– 3.0
$Al_2O_3 + Fe_2O_3$	0.2– 2.1	0.5– 1.3
$MgCO_3$	0.2– 4.2	1.0– 2.5

349. Argillaceous Limestone, Cement Rock. The term "cement rock" is technically applied to a limestone containing about 68 to 72 per cent of lime carbonate, 18 to 27 per cent clayey matter, and not more than 5 per cent of magnesium carbonate. Cement rock is a dark gray to black slaty limestone, softer than pure limestone and consequently more easily ground. As a rule the cement rock must be mixed with a comparatively pure limestone in small percentages. Some cement rock, however, contains an excess of calcareous material, necessitating the admixture of shale or clay.

350. Marl. Marls are deposits of comparatively pure carbonate of lime found in beds of existing or extinct lakes, and may be considered to be unconsolidated limestones. Organic matter, clay, and carbonate of magnesia are the principal impurities found in marls, with sometimes small amounts of sulfur. Marls usually analyze about 90 to 97 per cent $CaCO_3$ and $MgCO_3$, less than 1 per cent SiO_2, less than 1 per cent Al_2O_3 and Fe_2O_3 combined, the balance being made up of small amounts of organic matter, SO_3, etc. When used in the manufacture of Portland cement, marls usually require the addition of 15 to 20 per cent clay. The large percentage of water (often 50 to 60 per cent) usually present in the marl upon arrival at the plant is disregarded in the above statement of composition. Marls have the economic advantage of being naturally of fine particle size and require little or no reduction to make them suitable for burning. They may be obtained by simple methods such as dredging.

351. Clays, Shales, and Slates. Clays, shales, and slate may in general be considered of the same ultimate composition, differing only in the degree of consolidation. All clays are formed from the débris resulting from the decay of rocks, and hence they differ greatly in composition and physical character. Clays left where rock has disintegrated are called residual clays; those transported and deposited by stream action are sedimentary clays; and those deposited by glacial action are glacial clays. The different classes of clays differ in composition owing to differences in the manner of their deposition. Residual clays are likely to contain fragments of quartz, flint, or lime carbonate, depending upon the kind of rock disintegrated; sedimentary clays in their long water transportation usually have lost all their coarser material and so form a fine-grained homogeneous product; the glacial clays show even less homogeneity than the residual clays and are likely to contain much sand, gravel, and pebbles.

Absolutely pure clay is hydrated silicate of alumina ($Al_2O_3 \cdot 2\ SiO_2 \cdot 2\ H_2O$). Such a clay is not available for cement manufacture but it is imperative that the clay be as free as possible from gravel and sand. The proportion of silica should not be less than 55 to 65 per cent, and the combined amount of alumina and iron oxide should be between one-third and one-half the amount of silica. The presence of gypsum or pyrite in the clay is injurious, and magnesia and alkalies should not be present in quantities exceeding about 3 per cent.

Shales are clays hardened by pressure, but they have almost invariably been formed from deposits of sedimentary clay and so do not show the irregularities in composition common to most residual or glacial clays. Shales are preferable to soft clay for mixing with limestone because, on account of the similarity in physical characteristics, segregation of the two is less likely to take place. They also carry less water and therefore require less drying. Clay, on the other hand, is better adapted for use with marl.

The slates are clays which through heavy pressure have solidified in a markedly laminated structure and acquired the property of splitting readily into thin sheets. The slates find only a limited application in the manufacture of Portland cement.

352. Blast-furnace Slag. Three classes of cement which must not be confused are made with blast-furnace slag as one of the ingredients. One is the slag or puzzolan cement made by grinding blast-furnace slag with hydrated lime without subsequent calcination; a second is a true Portland cement made by mixing limestone and slag, grinding the mixture very finely, and calcining the product as in the usual process of Portland cement manufacture; the third is a cement made by grinding finely together 70 per cent of true Portland cement and 30 per cent of granulated blast-furnace slag.

Blast-furnace slag is a fusible silicate formed during the smelting of iron ore by the combination of the fluxing material with the "gangue" of the ore. The slags used in cement manufacture are those of strongly basic character, the higher the lime the better. The following analysis is typical of the slags used in the manufacture of cements of the second class above given.

Silica	33.10
Iron oxide and alumina	12.60
Lime	49.98
Magnesia	2.45

MANUFACTURE OF PORTLAND CEMENT

353. Principal Steps. The principal steps in the manufacture of Portland cement consist of quarrying, crushing, grinding, mixing, calcining, cooling the clinker, grinding the clinker, adding retarder, and packing.

354. Wet and Dry Process Manufacture. The treatment of the raw materials before calcination may be carried on by the *dry* or by the *wet* process. In the dry process the raw materials are dried before being ground and mixed; in the wet process the materials are ground and mixed wet.

The economics of manufacture favor one process over the other according to the raw materials available. If the available materials are cement rock and limestone which are naturally dry or contain so little free water that they may be dried by waste heat from the kilns so that they may be ground economically in a dry state, the dry process offers economy in the cost of grinding and burning. If, however, at least one of the components of the mixture is wet, such as a marl or a clay, the increased cost of drying the raw materials in the dry process would be relatively greater than the increased cost of burning wet materials in the wet process.

From the standpoint of chemical control of raw-material composition, there is little choice between the two processes when modern methods are employed. Under average conditions a wet-process operation is usually less complicated and better suited for the purpose of improving quality and increasing the variety of types of Portland cement which can be produced with available materials.

Dust conditions differ little in the two processes. The materials are wet only during preliminary treatment in a wet-process plant, the clinker being ground dry. If the raw-material mills of a dry-process plant are provided with proper dust-collecting equipment, a dry-process plant can be kept as clean as a wet-process one.

355. Quarrying, Crushing, and Drying the Rock. The raw materials employed in the dry process are usually in the form of more or less compact rock, either limestone and shale, or limestone and cement rock. Open quarry practice is usually followed, the rock being blasted down in benches, reduced to sizes suitable for handling by secondary blasting, loaded by power shovels onto quarry cars usually of steel side-dump type, and removed in the cars to the crusher.

Modern plants employ primary and secondary stages of crushing. The primary crusher is either of the jaw or gyratory type. There is little choice between the two except that the jaw crusher is easier to feed and will take larger stone in proportion to the size of the machine. The secondary crusher is ordinarily of the hammer type, but small gyratory crushers are often used. The degree to which crushing is carried varies at different plants, but it is considered good practice for power economy not to exceed a reduction of 4 or 5 to 1 in each stage. It is general practice to reduce the rock to a size that will pass a 2- or 2½-inch ring.

Storage facilities for the crushed stone are ordinarily provided so that the composition can be controlled. One type of rock storage involves the use of overhead bins from which withdrawals are made by weighing feeders, whereby the materials may be proportioned. Another type employs a covered craneway for the storage of crushed stone in separate stock piles arranged according to composition. Feed bins of the raw-material grinding mills are arranged under the craneway so that they can be filled by the grab bucket. Each raw mill is provided with two feed bins from which the rock is withdrawn by separate measuring feeders so that the composition can be held within close limits.

It is often necessary to dry the rock after crushing since the presence of moisture in the rock as it comes from the quarry impairs the efficiency of grinding and pulverizing machinery. The rotary type of dryer is used almost exclusively in cement mills. Steel cylinders, 50 feet in length and 5 feet in diameter, set at a slight inclination with the horizontal, are typical. Waste gases may be utilized.

356. Grinding, Mixing, and Pulverizing the Raw Materials. The further reduction of raw material after drying is carried on in two stages. In the first stage the materials, either mixed or separately, are ground to a size varying in the practice of different plants from ¼ inch down to $\frac{1}{20}$ inch or less. In the second stage the mixture of the constituent materials is pulverized to the final degree of fineness required. The choice of the type of grinding and pulverizing machinery is dependent upon the character of the raw materials.

The mixing of the two classes of raw material may take place at any one of several points in the process of preparing the material for calcination. The choice depends largely upon the relative physical characteristics of the two classes of material and their uniformity. Two rock ores, such as limestone and shale, or limestone and cement rock, may run so nearly constant in composition that the chemist's analyses made on material as it comes from the quarry may be trusted, and the mixture may be proportioned by weight either just before or immediately after crushing, without fear of segregation of the two rocks in subsequent handling. Such a combination as a limestone and a clay would give difficulty by segregation if mixed before being reduced to a finely divided state.

The point in the process where mixing is most often accomplished is immediately after preliminary grinding and before pulverization, an analysis of the materials having been made after grinding. In the extremely finely divided state attained in the process of pulverization, a very intimate mixture may be made without danger of segregation.

Dry raw material is mixed and blended by combining the output of several mills and circulating the material in storage. A modern method of blending consists of pumping the dry, finely divided materials into a group of storage silos and then withdrawing the materials from the bottoms of the silos. Dry, pulverized materials when mixed with air under certain conditions have the characteristic of increasing in bulk and becoming fluent to such an extent that they may be pumped in a manner similar to the way liquids are pumped. The materials when pumped into the storage silo flow to a level surface. The pulverized materials do not flow from the silo in the order of the lowermost materials in storage, but descend uniformly from all levels above the discharge spout, thus giving a cross-section of all the thin, flat layers.

Probably no other factor in the production of a satisfactory cement holds so important a place as the degree of fineness attained in grinding the raw mix. Since the temperature of calcination is simply a sintering temperature, and not sufficient to fuse the mixture and so produce a homogeneous product, diffusion between the lime and alumina and silica must take place at a temperature usually not exceeding about 1600° C. (2912° F.). The amount of diffusion in a solid is dependent upon the temperature, the time allowed, and the amount of surface exposed. Fineness of grinding will therefore lead to economy in calcination, since either the duration or the temperature of burning will be lessened by increased fineness.

The actual degree of fineness attained in practice is dependent upon the materials used and other local factors. The mixtures of cement rock with a relatively low proportion of limestone, for instance, require less fine grinding than the mixtures of two pure classes of material such as a pure limestone and a clay or shale. Ordinarily for proper calcination approximately 85 per cent of the raw mixture should pass a No. 200 sieve.

357. Proportioning the Raw Materials. The combining of the raw materials in such a manner as to achieve a desired ratio of calcareous to argillaceous materials is not a simple matter, for the reason that Portland cement after calcination is not a mixture of lime and clayey materials, but is what may be termed a "solid solution" of a number of components including silicates and aluminates of lime, but no free lime. The ratio of lime to clayey material previously cited very roughly expresses the relative proportions in which the two classes of material are understood to combine, and the actual proportions of two given materials which will produce a satisfactory cement can be determined only by a knowledge of the detailed composition of each of the component raw materials, and a further knowledge of the compounds which will be formed during calcination.

The application of a rule based upon complete analyses of the raw materials is not necessary once a plant is well established with fairly uniform raw materials. Usually a fixed standard total percentage of carbonate ($CaCO_3$ and $MgCO_3$) is found by experience with any given raw materials to give a satisfactory mixture, and this standard is thereafter maintained as long as the raw materials remain unchanged.

The usual method of control consists in the analysis of both raw materials at the plant before grinding, grinding and mixing according to these analyses, analyzing the mixture as a check, and correcting the mix by the addition of the constituent required before calcination.

358. The Wet Process of Manufacture. The same classes of raw materials as used in the dry process may be employed in the wet process, but, in general, the materials handled by the wet process are physically soft, such as marl with clay or shale, which in their natural state carry high percentages of moisture.

Marl usually not only is saturated with moisture, but often also is covered with water to a considerable depth. Under such circumstances it is obtained by dredging, and is pumped to the mill through a pipeline. The marl usually reaches the plant in the shape of a thin mud containing about 50 per cent water. It is passed through a separator to remove stones, roots, etc., and then stored in large tanks.

The clay upon arrival at the plant is often dried in order to facilitate the determination of the correct proportion to be added to the marl. It is then ground in an edge-runner mill between millstones, or in a disintegrator.

From the storage tank the marl is pumped into either a measuring tank or a weighing hopper. The ground clay is added to the marl in the proportion determined by analysis of the materials.

The mixture is then discharged into a pug mill, which consists of a horizontal cylinder within which two shafts provided with steel blades rotate. The mixture is churned up by the revolving blades, thoroughly mixed, and discharged into large tanks, where it is sampled, analyzed, and corrected by the addition of clay or marl. In order to prevent any part of the mixture from settling, it is necessary to provide these tanks with revolving paddles which keep the mass constantly agitated. The "slurry" is then passed on to the final grinding mill.

The output of the finishing mill is conveyed to supply tanks for the kilns and is usually charged in without any previous drying. It generally contains from 60 to 65 per cent of water, which must be evaporated in the upper part of the rotary kiln. This practice necessarily increases the fuel consumption of the kiln. In some plants water is removed by rotary dryers which utilize waste heat from the kilns.

359. Minerals Separation. This is a method which has been recently applied to raw materials in the wet process of cement manufacture for the purpose of eliminating relatively coarse silica which does not react uniformly in the cement. Calcite is separated by a process of froth flotation from quartz and mica by means of small quantities of collecting reagent such as fatty acid. Hydraulic classification can be combined with froth flotation to eliminate coarse particles in the raw-material mixture. This is a "subtractive" method of controlling the composition by eliminating undesirable constituents of the mixture, and it tends in general to give more accurate and economical results than "additive" methods in which other materials are added. Additive methods cannot satisfy all conditions since pure minerals are not available to the cement manufacturer because of their cost. The economical advantages of this minerals-separation method include use of raw materials of more variable composition and reduction in raw-material grinding since coarse material may be removed prior to burning.

360. Calcination. The principal objects accomplished by calcination of Portland cement mixtures are, in the approximate order of their sequence, the evaporation of water, the dissociation of carbonates of lime and magnesia, the expulsion of the alkalies, the oxidation of ferrous to ferric oxides, and the combination of lime and magnesia with silica, alumina, and ferric oxide to form the silicates, aluminates, and ferrites which make up Portland cement.

Most of the moisture is driven off at temperatures only slightly exceeding 100° C. (212° F.). Lime carbonate is dissociated at temperatures somewhat above 900° C. (1652° F.), and magnesium carbonate at temperatures probably between 800° C. (1472° F.) and 900° C. (1652° F.). The formation of silicates, aluminates, and ferrites does not take place at temperatures below about 1100° C. (2012° F.), and for most commercial cement mixtures the attainment of a temperature of about 1550° C. (2822° F.) has been found necessary in order to insure the combination of practically all the lime with the clayey constituents.

361. Burning the Cement Mixture. The cement mixture is calcined in a long horizontal rotary type of cement kiln which may be from 150 to 375 feet long and 5 to 12 feet in diameter. The steel drum of the kiln is lined with firebrick and is supported at intervals on rollers. The kiln is rotated at a speed of about ¾ revolution per minute and is inclined with the horizontal about ½ inch per foot.

Raw material is discharged into the upper end of the kiln from the supply bins either through an inclined spout or a water-jacketed screw-conveyor running through the stack flue. Usually the feeding device is belt-connected to the kiln drive so that the feeding starts and stops with the kiln.

Coal for kiln burning is usually gas slack and should contain as little ash as possible. It is usually crushed in rolls or pot crushers, dried in a rotary dryer, and pulverized in a tube mill or some other type of pulverizer, so that approximately 95 per cent will pass a No. 100 sieve.

The pulverized coal is delivered by conveyors from the coal-grinding mill to bins located above and behind the burner end of the kiln. A conveyor carries the coal from the supply bin to a point where it falls into an air injector, where it encounters an air blast which conveys it through a pipe to a nozzle projecting into the kiln.

Crude oil, when burned in the rotary kiln, is sprayed in by a blast of air from blowers or air compressors. In order to distribute the heat properly in the kiln, two or more oil burners are necessary.

Proper burning is determined by the color and appearance of the clinker, the properly burned clinker being a greenish black in color, having a vitreous luster, and showing bright, glistening specks when just cooled. Most of the lumps are the size of a walnut or smaller. Underburned clinker is brown or has brown centers, and lacks the luster of well-burned clinker. Overburned clinker has hard brown centers. Overburned clinker is probably not injurious except for very low-lime cements, but overburning means a waste of fuel and increases the expense of grinding, owing to the greater hardness of overburned clinker.

Under average conditions an 8-by-100-foot kiln should turn out about 600 barrels of cement per day with a fuel consumption of about 80 pounds of coal per barrel. A 9-by-150-foot kiln should turn out about 750 barrels per day.

The low heat efficiency attained in the rotary-kiln calcination of cement has led to a quite general effort to devise means of utilization of the waste heat.

Heat lost by radiation cannot be utilized but may be reduced by the placing of a poor heat conductor between the kiln lining and the shell. Heat carried away from the kiln in the stack gases may be reduced in some degree by lengthening the kiln, thereby utilizing a part of this heat in drying and preheating the raw material in the upper part of the kiln.

The heat carried by the stack gases has been used in two ways: the first and most common method is for the drying of the raw material in rotary dryers; the second method consists in passing the gases through vertical water-tube boilers, thus generating steam for the power plant. The principal difficulty encountered is the presence of large quantities of dust in the kiln gases, which makes impossible many ordinary methods of heat regeneration.

The utilization of the heat carried off by the hot clinker is quite common. In general, the method consists in drawing the air for combustion in the kiln through the hot clinker in a rotary cooler, thus cooling the clinker and preheating the air.

362. Treatment of the Clinker. The clinker as it issues from the kiln is very hot and must be reduced to a suitable temperature before being ground. Occasionally it is the practice of cement plants to allow the clinker to cool in piles outside the mill. More generally, however, it has been found advisable to adopt some type of mechanical cooling device which may or may not provide for the recovery and utilization of the heat carried off by the hot clinker.

It is the usual practice to grind the clinker by the same type of grinding machinery as in the raw-material mill, the grinding and pulverizing being accomplished in two separate stages.

Air separation methods are employed in modern plants to withdraw the fine materials from the grinding mills, thus eliminating the cushioning effect of the fine materials, controlling the temperature of the materials, and avoiding waste of power. Air separation provides a uniform method of obtaining a cement of high surface area and is especially important in the production of high-early-strength cement.

363. Addition of Retarder. The clinker produced in the rotary kiln makes a cement which is naturally very quick-setting. In order to retard its set sufficiently to enable it to meet commercial requirements, it is the universal practice to add sulfate of lime either before grinding or between the stages of grinding and pulverizing the clinker.

The retarder is added in the form of raw gypsum ($CaSO_4 + 2\ H_2O$). The gypsum, in the form of lumps crushed to pass a 1-inch ring, is added to the clinker either by hand or by mechanical weighing devices, the quantity being, as a rule, about 2 per cent, and never exceeding 3 per cent.

364. Storing and Packing. The finished cement is stored in silos from which it is withdrawn by conveyors or pumps and delivered to packing bins, or pumped directly in bulk to box cars, tank cars, special trucks, ships, and barges. Bulk cement is employed in the construction of most large concrete structures for economy, bulk shipments representing about 40 per cent of the total in the United States. Cement may be packed in wooden barrels containing 376 pounds net but generally is packed in cloth or paper bags containing 94 pounds net. The bags are sealed by wiring or sewing before filling and are filled through a self-closing valve in the bottom by means of a packing machine.

CONSTITUTION OF PORTLAND CEMENT

365. Composition. A study of a large number of analyses of commercial cements shows that the range in composition is comparatively limited. Table XXXIII gives the variations for American Portland cement.

TABLE XXXIII

RANGE IN COMPOSITION OF PORTLAND CEMENT

Constituent	Percentages	
	Lowest	Highest
SiO_2	19.56	24.48
$Al_2O_3 + Fe_2O_3$	6.46	13.74
CaO	58.07	64.96
MgO	0.61	3.53
Alk	0.40	2.25
SO_3	0.25	2.86

366. Properties of Compounds. Five major compounds are known to be present in Portland cement after calcination: tricalcium silicate, dicalcium silicate, tricalcium aluminate, tetracalcium aluminoferrite, and magnesia. These compounds are normally present in the clinker in the form of extremely fine interlocking crystals, although some amorphous material is frequently present. Magnesia appears to exist uncombined in Portland cement. It is nearly inert though if present in excess amount it might cause unsoundness due to extremely slow hydration. Magnesia should not be present in excess of 5 per cent. The characteristics of the other four major compounds are compared in Table XXXIV.

TABLE XXXIV

CHARACTERISTICS OF MAJOR PORTLAND CEMENT COMPOUNDS[1]

	Tricalcium Silicate C_3S	Dicalcium Silicate C_2S	Tricalcium Aluminate C_3A	Tetracalcium Aluminoferrite C_4AF
Cementing value	Good	Good	Poor	Poor
Rate of reaction	Medium	Slow	Fast	Slow
Amount of heat liberated	Medium	Small	Large	Small

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[1] R. W. Carlson: Development of Low-heat Cement for Mass Concrete, *Engineering News-Record*, October 20, 1932, p. 461.

The calcium silicates are the effective cementing materials; the other compounds are generally believed to have little if any cementing value. All these compounds liberate heat during hydration, the total amount of heat liberated being, in general, proportional to the rate of chemical reaction.

367. Tricalcium Silicate. When water is added to tricalcium silicate ($3CaO \cdot SiO_2$), a moderately rapid reaction occurs, both by hydrolysis and hydration. This reaction may be expressed approximately as

$$3CaO \cdot SiO_2 + H_2O = 2CaO \cdot SiO_2 \cdot xH_2O + Ca(OH)_2$$

One molecule of CaO splits off, and the products are crystalline calcium hydroxide and a less basic amorphous hydrated calcium silicate of composition represented by the formula $2CaO \cdot SiO_2 \cdot xH_2O$. This compound is a gel. To its formation is due the greater part of the early strength of the cement and some of the early heat evolution. Tricalcium silicate has good cementing value.

368. Dicalcium Silicate. In the presence of water $2CaO \cdot SiO_2$ hydrates slowly to form directly a compound of the composition $2CaO \cdot SiO_2 \cdot xH_2O$. This is similar to and possibly identical with the compound formed by the hydrolysis of $3CaO \cdot SiO_2$. Dicalcium silicate hydrates slowly, chiefly after the first week, and very little of the strength attained by the cement in 28 days is attributable to it, but the greater part of subsequent increases is due to it.

369. Tricalcium Aluminate. This compound hydrates very rapidly with water, chiefly in the first day, to form hydrated tricalcium aluminate; several different crystalline hydrates have been identified, the formula being $3CaO \cdot Al_2O_3 \cdot 6H_2O$. The reaction is accompanied by a considerable evolution of heat, and the mixture sets almost instantly. In the presence of gypsum the heat evolution is less, and the setting occurs more slowly. This is due to the formation of calcium sulfoaluminate, $3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 31H_2O$. As long as the water contains dissolved gypsum the calcium sulfoaluminate forms in preference to the hydrated tricalcium aluminate. It is to retard the rapid hydration of the aluminate that gypsum is added to commercial cement clinker. Tricalcium aluminate has poor cementing value. All properties of cement, including volume constancy and durability, being taken into consideration, tricalcium aluminate is believed to be the least desirable of the four major cement compounds.

370. Tetracalcium Aluminoferrite. This compound hydrates slowly, and since it is considered to have no great cementing value it is believed to be of minor importance. The reactions of $4CaO \cdot Al_2O_3 \cdot Fe_2O_3$ with moderate quantities of water have not been completely learned. The reaction appears to be a hydrolysis resulting in the formation of hydrated tricalcium aluminate and an amorphous material of undetermined composition.

371. Gel Theory of Cement Hardening. The gel theory, advanced by Michaelis in 1893, explains the hardening of cement concrete by the formation of a colloidal gel which grips the aggregate and the unhydrated particles of cement. According to this theory crystallization does not take place until after the cement hardens. When water is added to cement, it begins to dissolve the surfaces of the particles. The substance thus produced forms a colloid which coats the cement grains and causes them to adhere. The colloid appears to grow out from the unhydrated centers of the grains, the temperature increases, and as the cement loses plasticity it is probable that the colloid becomes a gel. The grain centers can be hydrated only as water slowly passes through the relatively impermeable gel. As long as the gel is wet and jelly-like the cement is not hard, but when the gel dries out the cement hardens. The water in the gel may evaporate as when cement is cured in air or it may be adsorbed on the unhydrated centers of the cement grains, thus dissolving the surface and producing new colloid which is adsorbed by the gel already formed and producing saturated solutions which crystallize. The hydration of the grains uses up the water in the gel faster than it can be supplied through the colloidal gel coatings, thus producing a hard gel. The gel reacts in this manner even when the cement concrete is immersed in water. The gel cannot be softened again by water absorption after hardening and hence may be termed an irreversible colloid. However, there appears to be a movement of water in cement concrete for a long time, the hydration of cement and formation of gel continuing indefinitely, although the process slows down as the cement grains grow smaller and the gel becomes denser. A contributing factor to this phenomenon of continuous hydration is the growth of crystals in the micropores which compresses the gels and squeezes out water which acts to hydrate more cement.

372. High-early-strength Portland Cement. This cement is manufactured to meet the demand for an early use of the fabricated concrete structure instead of waiting for days, or sometimes several weeks, for the concrete to harden sufficiently. This early strength of the cement is attained by changing the proportions and adding other materials, by finer grinding, and by better burning. In many cases the composition is varied so as to give a relatively large percentage of tricalcium silicate and a correspondingly low percentage of dicalcium silicate. Double burning and triple grinding are examples of the changes in the manufacturing processes to produce this result.

373. Low-heat Portland Cement.* Low-heat Portland cement has been developed in recent years for use in concrete structures of large

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* R. W. Carlson: Development of Low-heat Cement for Mass Concrete, *Engineering News-Record*, October 20, 1932, p. 461.

mass such as dams. The purpose of this cement is to reduce the amount of heat generated by the hydrating cement during the period of hardening, thereby decreasing the amount of expansion and subsequent contraction of the concrete. The heat liberated by chemical action during hydration of the cement is dissipated rapidly in the relatively thin sections employed in most concrete work, and volume changes other than those due to stress are caused principally by variation in moisture content. In mass concrete, however, the interior of the concrete dries very slowly, if at all, and the principal volume changes are caused by variations in temperature which accompany the liberation of heat by the hydration of the cement and the dissipation of this heat from the concrete. Increase in the size of mass-concrete structures, acceleration of construction speed, and increased activity of present-day Portland cements have tended to increase the probability of cracking in large concrete masses. The problem of correcting this tendency to crack consists essentially of reducing the effects of heat of hydration of the cement.

A comparison between a typical low-heat Portland cement and a standard Portland cement is given in Table XXXV, which is taken from an article by R. W. Carlson.* The low-heat cement has a low percentage of the troublesome compound, tricalcium aluminate, and a relatively low percentage of tricalcium silicate which liberates a medium amount of heat during hydration, but has a relatively high percentage of dicalcium silicate which liberates a small amount of heat during hydration. Such a low-heat cement would be slow in hardening owing to the small amount of tricalcium silicate, but satisfactory ultimate strength is assured by the large amount of dicalcium silicate whose hydration occurs chiefly after the first week. Slow hardening is not undesirable in mass-concrete construction, but may even be advantageous since the entire concrete mass composed of sections cast at different times may expand and contract more nearly as a unit. The changes in chemical composition also permit fine grinding of the cement, giving the advantage of increased workability, strength, and watertightness. Such a low-heat cement might not be desirable for general construction work because of its characteristics of slow hardening. Moderate-heat cement which has properties intermediate between those of low-heat and standard Portland cements has been used to a considerable extent. (See Table XXXV.)

PROPERTIES OF PORTLAND CEMENT

374. General. The value of cement depends primarily upon its mechanical strength when hardened.

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* R. W. Carlson: Development of Low-heat Cement for Mass Concrete, *Engineering News-Record,* October 20, 1932, p. 461.

TABLE XXXV

COMPARISON OF STANDARD AND LOW-HEAT PORTLAND CEMENTS

Cement	Tricalcium Silicate, per cent	Dicalcium Silicate, per cent	Tricalcium Aluminate, per cent	Fineness, Passing No. 200 Sieve, per cent	28-day Compressive Strength of 1 : 3 Mortar, lb. per sq. in.	28-day Heat Generation, calories per gram cement
Standard (1932)	55	23	11	90	4000	100
Low-heat for Pine Canyon Dam (1932)..	30	46	5	92	2500[1]	75[2]

[1] Expected average; specified minimum of 2000 lb. per sq. in.
[2] Expected average; specified maximum of 80 calories per gram.

The establishment of the existing standards for physical and mechanical properties has for its object the fixing of values readily determined in the laboratory for cements found satisfactory in practice. The results of laboratory tests of cement cannot be considered to represent the properties of the material under working conditions, the quantitative results obtained having only a relative value.

The physical properties utilized for comparative purposes are: fineness, time of setting, and soundness; the mechanical properties are the tensile and compressive strengths of standard sand mortars.

375. Setting and Hardening. When a true hydraulic cement is gauged with sufficient water and then left undisturbed, it soon loses its plasticity and reaches a state in which its form cannot be changed without producing rupture. This change in condition is known as the *setting* of cement and has usually been considered somewhat distinct from *hardening*. Setting usually takes place in a few hours or even minutes, whereas hardening may proceed for months or years.

376. Specific Gravity. The significance of the specific gravity of a cement was formerly considered to be its usefulness in detecting adulteration and underburning. More recently, investigations have shown that the principal factor influencing specific gravity is the degree of seasoning of cement. Specific-gravity tests will not detect underburning and will detect adulteration only in respect to a few classes of adulterants. Its importance, therefore, may be considered to be very limited.

Until recently it was specified * "that the specific gravity of Portland cement shall not be less than 3.10." Experience has shown that this property is of little value and the test is no longer required.

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* Unless otherwise noted, specifications for cement are those of the American Society for Testing Materials.

377. Fineness of Grinding. Experiments have shown that the coarser particles of cement are inert. Even a sieve having 325 meshes per linear inch is not fine enough to separate the inert from the active material. This separation can be effected only by some suspension method which retains nothing but the impalpable powder, or flour.

The approximate percentages of cement for sizes finer than the No. 200 sieve can be determined by means of the air analyzer developed by the Bureau of Standards. The sample of cement, placed in a bulb at the base of a tube, is agitated by a jet of air through a glass nozzle. The fine part is blown up the tube into a container at the top. A larger-size nozzle will blow out the coarser material in turn. By this means it is possible to separate the fine particles, or flour, into many sizes.

The American Society for Testing Materials has developed a tentative method of test for fineness of Portland cement by means of the turbidimeter which consists essentially of a source of light of constant intensity adjusted so that approximately parallel rays of light pass through a suspension of the cement to be tested and impinge upon the sensitive plate of a photoelectric cell. The current generated by the cell is measured with a microammeter, the indicated reading being the measure of the turbidity of the suspension. Turbidity is in turn a measure of the surface area of the suspended sample of cement. The fineness of Portland cement as represented by specific surface is expressed as total surface area in square centimeters per gram of cement.

The fineness of cement is also determined by the hydrometer method. The grain-size distribution of the cement can be determined by taking density readings on a hydrometer immersed in a suspension of the cement at definite time intervals.

Stokes' law for the settling velocity of spheres in a fluid is used to compute the grain-size distribution in the air analyzer, turbidimeter, and hydrometer methods.

The maximum degree of fineness compatible with reasonable manufacturing costs is desirable. The strength, except in neat tests, is greatly increased and the sand-carrying capacity and the mortar strength very materially increased by increased fineness of grinding; the time of setting is materially shortened.

"In general, the strength of concrete increases with the fineness of a given lot of cement. There is no relation between the strength of concrete and the fineness of cement, if different cements are considered." *

A small fraction in the neighborhood of 5 microns and lower is necessary in order to develop substantial strength within a day. The fractions from this point to 15 microns may be classed as the most important

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* Duff A. Abrams: Effect of Fineness of Cement, *Proc. Am. Soc. Test. Mats.*, 1918.

source of ultimate strength. They progress in strength rapidly, passing the small-sized fraction in about 3 days and are not passed by any other fractions at any period up to a year, at least. These characteristics are principally attributable to the surface area with relation to weight, but are influenced in lesser degree by variations in compound composition between various fractions owing to relative differences in grindability of the compounds. For example, tricalcium silicate tends to increase slightly in percentage proportion in the finer fractions.

378. Time of Setting. The rapidity with which a cement sets is simply a criterion by which its suitability for use under given conditions may be determined. The time of set is often an important consideration in the choice of a cement for a particular purpose, and on account of the effect of storage upon the setting time the test should preferably be made after delivery of the cement on the work. The effect of temperature and the percentage of water used in mixing, as well as the humidity of the air, is so marked that the determination of the setting time must always be made with extreme care under standardized conditions. No analogy can be traced between the rapidity with which a cement sets and the strength it will ultimately develop.

Specification. "The cement shall not develop initial set in less than 45 minutes when the Vicat * needle is used or 60 minutes when the Gilmore † needle is used. Final set shall be attained within 10 hours."

So many factors influence the time of setting, such as temperature, amount of gauging water, presence of sulfates, etc., that no general statement can be made as to the rate of setting of Portland cements. In general, the higher the temperature the quicker the set will be.

The percentage of water used to gauge cement influences its time of set to a very marked degree, a wet mix setting much more slowly than a dry one. It is on this account that tests for time of set are always made with a paste possessing a standard degree of plasticity (a normal consistency mix). Normal consistency is determined by means of the Vicat apparatus, in which a standard cylinder 1 centimeter in diameter, weighing 300 grams, is allowed to penetrate neat cement paste held in a standard rubber ring. For normal consistency the cylinder should penetrate 10 millimeters in 30 seconds. The water required for normal consistency is usually between 20 and 28 per cent.

The addition of 1½ to 3 per cent of plaster of Paris or gypsum to the clinker before grinding is necessary in order to retard the set sufficiently to pass the requirements of commercial use.

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* *Vicat needle.* Diam. = 1 mm. Wt. = 300 grams. For initial set the needle stops 5 mm. above glass in ½ minute. For hard set the needle does not penetrate.

† *Gilmore needles.* For initial set 1/12-in.-diameter needle with a weight of ¼ lb. does not penetrate. For hard set 1/24-in.-diameter needle with a weight of 1 lb. does not penetrate.

379. Tensile Strength of Neat Cement. The tensile strength of cement is in itself of very little importance, because cements are rarely called upon to withstand tensile stresses. The significance of tensile strength as revealed by laboratory tests is therefore limited to the assumption that there exists some relation between tensile strength, compressive strength, and soundness.

The relation between tensile strength and compressive strength is by no means constant at all ages, and it also varies with different cements and with different mixtures. There is no ground for concluding that a high tensile test of cement at the usual age of testing indicates soundness. The neat tensile strength is no indication of the strength of the cement in mortars and concrete, and this test has, therefore, been discontinued as a standard.

Tests of tensile strength are dependent upon a great many factors which influence the accuracy of the results. Perhaps the greatest of these is the personal equation. In addition to the personal factor, tensile strength is influenced by the amount and the temperature of gauging water, the method of mixing and molding in general, the temperature and humidity of the air, the form of briquet, the design of the testing machine, and the manner of storage of the briquets prior to testing. Fine grinding is not beneficial to neat tensile strength, but materially improves the strength of mortars.

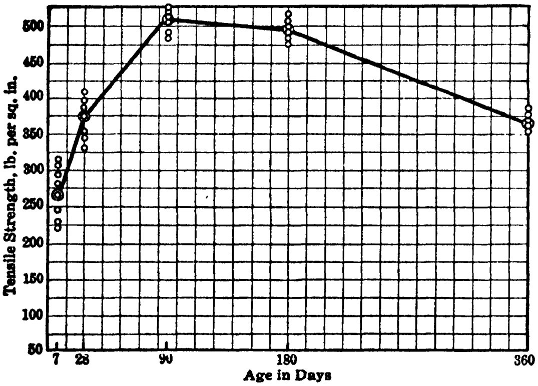

FIG. 97.—Tensile Strength of 7 Portland Cement Mortars (1 : 3) Standard Sand.

380. Tensile Strength of Standard Sand-cement Mortars. If tensile tests of cements are to be depended upon, the test pieces should be mortar briquets.

The amount of water to be used in gauging mortar for briquets is very carefully standardized and is based upon the water necessary to bring the neat cement to normal consistency.

Fig. 97 shows the average tensile strength, in 1 : 3 standard sand mortar, of seven brands of cement.

Specification. "The average tensile strength in pounds per square inch of not less than three standard mortar briquets composed of 1 part cement and 3 parts standard sand, by weight, shall be equal to or higher than the following:

Age at Test, days	Storage of Briquets	Tensile Strength, lb. per sq. in.
7	1 day in moist air, 6 in water	275
28	1 day in moist air, 27 in water	350

"The average tensile strength of standard mortar at 28 days shall be higher than the strength at 7 days.

"The sand to be used shall be natural sand from Ottawa, Ill., screened to pass a No. 20 sieve and retained on a No. 30 sieve."

381. Compressive Strength. Compressive strength is the best criterion by which to judge the value of a cement, as the conditions of testing more nearly approximate the conditions met by the material in use. As in tensile tests, the strength of neat cement in compression is of little importance, and tests should be made upon standard sand mortars. The tentative standard of the American Society for Testing Materials requires the use of 2-inch mortar cubes. The sand specified is a natural silica sand from Ottawa, Ill., graded as follows:

RETAINED ON	PER CENT
No. 100 sieve	98 ± 2
No. 50 sieve	72 ± 5
No. 30 sieve	2 ± 2
No. 16 sieve	0

The proportions of the standard mortar are 1 part cement to 2.77 parts graded Ottawa sand by weight and 53 per cent water by weight of cement (water-cement ratio of 0.8 by volume). The fabrication, curing, and method of testing of the cubes are specified.

382. Soundness. Soundness in a cement implies the absence of those qualities which tend to destroy its strength and durability and is one of the most important properties of cement.

Unsoundness is manifested by a lack of constancy of volume, disintegration being caused almost entirely by expansion occurring after the cement has set.

Since any amorphous hydrate shrinks during drying and expands when wet, it is evident that this behavior on the part of the amorphous hydrated constituents of gauged cements must cause shrinkage of neat cement in air and expansion in water. These changes in volume are very much lessened by mixing with inert material as in sand mortar, the degree of volume change being dependent upon the richness of the mortar. The result of the desiccation of the cement is the appearance of fine hair-cracks on the surface of cement or rich mortar used as a plaster or top coat. These fine hair-cracks should not be taken to be an indication of defective cement, but their appearance simply is an indication of too rich a mixture.

Unsoundness is due to disruptive action caused by crystallization of certain constituents of the cement. The principal constituent so involved is lime present in the free state. Proper burning and fine grinding, at least to such a degree that the calcareous particles are of a size suitable for reaction, tend to reduce unsoundness due to the presence of free lime.

A hard-burned calcium oxide has been discovered in Portland cement which hydrates so slowly that its complete hydration in concrete may be delayed probably up to 2 years. The effect is a disintegration of the concrete in the form of characteristic cracks.

The presence of excess dehydrated magnesia may also be the cause of unsoundness. In this event, unsoundness will be observed after a much longer period, since magnesia which has been highly heated remains inert for a long time before undergoing hydration.

The presence of excess sulfates is also thought to be the cause of unsoundness. The expansion is not due in this case to the hydration of lime sulfate, but is attributed to the formation of calcium-sulfo-aluminate, which is dangerous only in large quantities. The standard specifications limit the SO_3 to 2.00 per cent.

Specification. "A pat of neat* cement of normal consistency shall remain firm and hard, and show no signs of distortion, cracking, checking, or disintegration in the steam test for soundness."

The pat should be made on a clean glass plate and should be about 3 inches in diameter, ½ inch thick at the center, and taper to a thin edge. It is stored for 24 hours in moist air and then placed in an atmosphere of steam above boiling water for 5 hours.

This standard soundness test may show unsoundness due to the presence of free lime, but will not indicate unsoundness due to other constituents such as hard-burned calcium oxide, magnesia, and lime sulfate.

In order to determine the effects of these constituents upon unsoundness, studies of an accelerated soundness test conducted on neat cement bars in an autoclave have been carried on by Committee C-1 on Cement of the American Society for Testing Materials. Portland cement is subjected to the autoclave test at many cement plants before being distributed for use. The bars are 1-inch square, 11¼ inches long, and have ¼-inch stainless-steel reference plugs at each end which project $^3/_{16}$ inch beyond the end of the bar. The distance between embedded ends of the plugs is 10 inches, which is considered the effective length of the specimen.

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* Pure cement without addition of sand, etc.

The neat cement paste of normal consistency is mixed according to A.S.T.M. standard procedure and tamped uniformly in the molds. The cement bars are stored 24 hours in moist air, placed in water at 21° C. (70° F.) for 1 hour, and then surface-dried and measured for initial length and weight. The bars are then placed in an autoclave, heated to 218.3° C. (425° F.) in 1 hour, held for 3 hours by means of an automatic controller at this temperature, which corresponds to a pressure of about 300 pounds per square inch, and then cooled in another hour to a temperature of 65.6° C. (150° F.). The autoclave should preferably be electrically heated; the pressure chamber is a thick-walled steel cylinder, with its flange an integral part of the chamber. A thick steel cover is held in place during the test by steel bolts. A safety valve should be provided to guard against hazard from excess pressure. The bars are then put in hot water and the container is placed in moist air until cooled to 21° C. (70° F.). The final measurements of length and weight of the neat cement bars are made at a temperature of 21° C. (70° F.) by means of a measuring instrument equipped with a dial graduated to 0.0001 inch.

Tests by H. J. Force * indicated that cements which pass the autoclave requirements are more uniform and yield higher compressive strength than those which fail in this test.

383. The Expansion and Contraction of Cement and Mortar. Changes of temperature are accompanied by changes in volume in cements and mortars as in other structural materials. The temperature coefficient for mortars has been found to be 0.0000099 per degree C. (0.0000055 per degree F.).

Other volume changes due to the chemical processes of setting and hardening, and still others caused by variation in the moisture content of cement, constitute important considerations in the use of mortars and concrete. Professor A. H. White of the University of Michigan has made an experimental study of this question, and the following short discussion is based upon his work.

Fig. 98 shows the average percentage of linear shrinkage of bars of neat cement kept in air for periods up to 4 years, and also the average linear expansion of bars kept in water for 3 years. Four different brands of Portland cement, all passing standard specifications for constancy of volume, were used.

It is evident that in neat cement fully one-half the total expansion or contraction comes in the first month, and there is very little change after 1 year. The expansion and contraction of 1 : 3 mortar was found to be very much less than that of neat cement and, in general, at the end of 1 year amounts to one-quarter to one-third that of neat cement.

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* H. J. Force: Results Obtained with Autoclave Tests for Cement, *Proc. Am. Soc. Test. Mats.*, v. 13, 1913, p. 740.

When bars of cement or mortar, after lying in water for 3 years, were allowed to dry in air at room temperatures, they gradually contracted till, at the end of 2 months, they had shrunk not only to their initial volume, but in most cases showed a considerable further contraction. When the bars so air-dried were again immersed in water they recovered in 1 day 90 per cent of the length they had lost in 65 days' air-drying, and, for most bars, the length within 1 month exceeded that which they showed at 3 years before having been air-dried.

This alternate swelling and contracting of mortars may be explained by the gel theory. Water acts on the clinker until the gel becomes packed so tightly that no more water can force its way through. The cement or concrete will retain this condition unchanged as long as it is immersed in water. If the water is removed by evaporation, the dehydrated gel shrinks and the mass becomes porous. When it is again immersed in water, capillary action carries the water rapidly through the shrunken colloid to the particles of unchanged clinker, with the result that additional hydration products are formed. White found that the gel retains this reversibility at atmospheric temperature for at least 20 years.

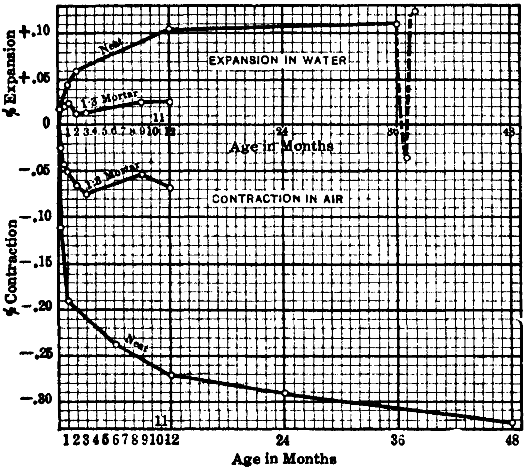

FIG. 98.—Linear Expansion and Contraction of Bars of Cement and 1 : 3 Standard Sand Mortar. (Tests of A. H. White.)

White's tests give indications of the influence of chemical composition on volume change. He reported that free lime causes an unusually large expansion during the first few weeks in water, but that hydration was complete within a year, and volume changes beyond that time were normal; bars of neat cement shrink when allowed to remain in air, but when much free lime is present, there may result a contraction for only a few weeks followed by expansion brought about by the continued hydration of the free lime. Free magnesia hydrated slowly and caused only slight expansion in water during the first 3 years, but when present in amounts above about 5 per cent, marked expansion occurred in water during the third to tenth years. Increase in the ferric oxide content of the cement tended to decrease the volume changes. The cements which were found to be most nearly constant in volume were relatively low in alumina content and contained a larger percentage of ferric oxide than of alumina. Portland cements high in alumina gave relatively large volume changes.

384. U. S. Government Cement Specifications. The technical requirements of United States Government specifications for four classes of Portland cements are given in Table XXXVI. These specifications require that all cements meet the A.S.T.M. requirements for soundness and for time of setting by the Gilmore needle.

Additions During Grinding. The above-referred-to Federal specifications for four classes of Portland cement permit water and/or any variety of calcium sulfate to which no additions have been made to be used in amounts such that the limits for ignition loss and sulfuric anhydride shall not be exceeded. The use of materials other than water and calcium sulfate may be permitted when specifically called for by the purchaser, in which case he must state the nature and quantity of the materials permitted.

385. Adhesive Strength of Cement and Mortars. *Adhesion to Brick.* The adhesion of cement and mortar to brick is of importance in all brick masonry construction. Table XXXVII has been constructed from a series of tests made by Sabin. In each test two bricks were cemented together flatwise with a ¼-inch mortar joint and pulled apart in tension after a given interval. The specimens were stored in damp sand after the first 48 hours, and tensile tests of the same mortar were made for purposes of comparison on briquets stored in the same manner. The consistency of the mortars was rather more moist than normal.

It will be noted that in general there is a fairly close relation between tensile strength and adhesion at all ages, the percentage of adhesion to cohesion being about 8.6 for neat cement, 7.1 for 2 : 1 mortar, 5.2 for 1 : 1 mortar, 4.8 for 1 : 2, and 3.8 for 1 : 3, showing that the addition of sand decreases the adhesion to brick more rapidly than it does the cohesive strength. Tests made with mortars to which lime paste had been added showed that the addition of 10 per cent lime increased the adhesive strength 120 to 140 per cent; 16.7 per cent lime, 130 to 160 per cent; 25 per cent lime, 110 to 120 per cent; and 50 per cent lime, 75 to 80 per cent. The addition of lime increased the ratio of adhesion to cohesion in all percentages, since only small percentages of lime are even moderately beneficial to tensile strength and large percentages are detrimental

TABLE XXXVI

TECHNICAL REQUIREMENTS OF FEDERAL SPECIFICATIONS FOR PORTLAND CEMENTS SEPT. 30, 1936

	Portland Cement	High-early-strength Portland Cement	Moderate-heat-of-hardening Portland Cement	Sulfate-resisting Portland Cement
	Not more than	Not more than	Not more than	Not more than
Loss on ignition, per cent....	3.00	3.00	3.00	3.00
Insoluble residue, per cent....	0.75	0.75	0.75	0.75
Sulfuric anhydride (SO_3), per cent....................	2.00	2.50	2.00	1.75
MgO, per cent.............	5.00	5.00	5.00	4.00
Al_2O_3, per cent.............	7.50	7.50	6.00	4.00
Fe_2O_3, per cent.............	6.00	6.00	6.00	4.00
$3CaO \cdot Al_2O_3$,[1] per cent.......	15.00	15.00	8.00	5.00
SiO_2, per cent, not less than....	....	....	21.00	24.00
Ratio Al_2O_3 to Fe_2O_3.........	....	....	0.7 to 2.0	0.7 to 2.0
Fineness, sq. cm. per gm., not less than...............	1500	1900	1800	1800
Heat of hydration in calories per gram, not more than....	....	....	70 at 7 days 80 at 28 days	....
Tensile strength, 1–3 standard sand mortar briquets, lb. per sq. in., not less than Age at test, 1 day......	....	275	....	....
3 days.....	175	375	125	....
7 days.....	275	425	250	175
28 days.....	350	....	325	300
Compressive strength, 1–2.75 fine testing sand mortar cubes, lb. per sq. in., not less than Age at test, 1 day......	....	1250	....	....
3 days......	900	2500	750	....
7 days......	1800	3500	1500	1000
28 days.	3000	....	2500	2200

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[1] The expressing of chemical limitations by means of calculated assumed compounds does not necessarily mean that the oxides are actually or entirely present as such compounds. The tricalcium aluminate is calculated according to the following formula:

$$\text{Per cent } 3CaO \cdot Al_2O_3 = 2.65 (\text{Per cent } Al_2O_3 - 0.64 \text{ per cent } Fe_2O_3)$$

TABLE XXXVII

ADHESION OF CEMENT AND MORTARS TO BUILDING BRICK

Adhesion or Cohesion	Age, months	Tensile Strength, lb. per sq. in., of Mortars Containing Parts Sand to 1 Cement				
		None	½	1	2	3
Cohesion	1	632	596	589	409	270
Adhesion	1	48	42	24	20	11
Cohesion	3	676	728	694	423	325
Adhesion	3	64	52	41	24	12
Cohesion	6	723	764	679	524	374
Adhesion	6	50	56	39	20	14

Adhesion of Mortar to Various Materials. The adhesion of mortars to various building materials is a matter of much importance in construction work, but it has been little investigated. Fig. 99 shows the results of tests made by General Wheeler.

Disks of the material concerned were prepared, 1 inch by 1 inch square and ¼ inch thick, and inserted in the center of the briquet molds, which were subsequently filled with mortar and tested in the usual manner in tension.

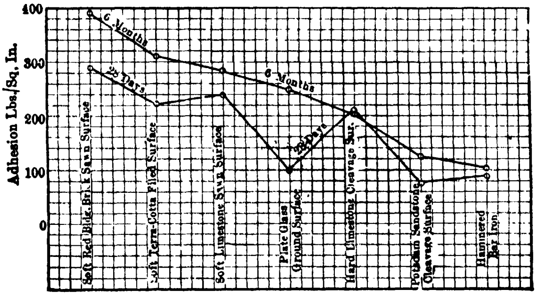

FIG. 99.—Adhesive Strength of Portland Cement: 1 part cement, 1 part crushed quartz. (Wheeler, Report of Chief of Engineers, 1895.)

386. Hydrated Lime. The addition of hydrated lime in small percentages to cement and mortars usually has a very appreciable effect upon the resultant tensile strength. The curves of Fig. 100 show the injurious effect on neat cement and the slightly beneficial effect, in amounts up to 15 per cent, on 1 : 3 mortar using standard Ottawa sand.

The addition of hydrate makes a fat, viscous mortar in which the sand and cement will not separate to as great an extent as when Portland cement is used with sand alone. This tends toward the production of a mixture of greater uniformity and with less voids, therefore securing a mortar of more uniform strength.

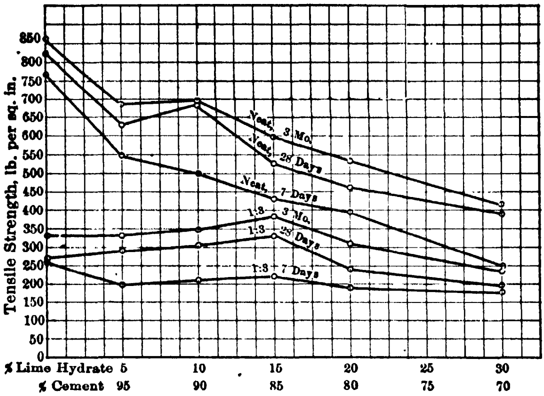

FIG. 100.—Effect of Hydrated Lime on Tensile Strength of Portland Cement and Mortars. (Gardner.)

PORTLAND-PUZZOLAN CEMENT

387. Definition. Portland-puzzolan cement may be defined as an intimate mechanical mixture of Portland cement and puzzolan, the materials having been pulverized before, during, or after mixing.

The puzzolan may be a natural or artificial material, and may be either calcined or uncalcined prior to being mixed with Portland cement. Puzzolan is usually added in amounts ranging from 10 to 30 per cent by weight of finished cement.

388. Properties. Laboratory tests * indicate that Portland-puzzolan cements as a group are more grindable, produce more plastic and more impermeable concretes, and generate less heat of hydration than Portland cements as a group, but the Portland-puzzolan cements require more water to produce concrete of a given consistency and exhibit greater shrinkage of mortar upon drying. In general, for rich mixes the compressive strength of concrete is less for Portland-puzzolan cements than for Portland cements, but the former show greater compressive strength for lean mixes at the later ages if active puzzolans are employed.

Portland-puzzolan cements containing active puzzolans high in silica exhibit materially greater resistance to the action of sodium sulfate than the corresponding Portland cements; the larger the percentage of puzzolan up to 30 per cent, the greater the resistance.

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* R. E. Davis, J. W. Kelly, G. E. Troxell, and H. E. Davis: Properties of Mortars and Concretes Containing Portland-Puzzolan Cements, *Jour. Am. Conc. Inst.*, v. 32, September-October, 1935, p. 80.

In Portland-puzzolan cements, the diatomaceous silicas as a group exhibit the highest degree of grindability, strength, and resistance to sodium sulfate; but this group also exhibits great contraction of mortar upon drying. The volcanic silicas as a group also exhibit high grindability, strength, and sulfate resistance; and the contraction of mortar upon drying is considerably less than for the diatomaceous silicas. Of this group, basaltic tuff is relatively low in grindability and sulfate resistance.

Calcination of the puzzolan reduces shrinkage of mortar upon drying and increases the sulfate resistance for puzzolans of diatomaceous silica and clay, but decreases the sulfate resistance for puzzolans of pumicite and tuff.

Portland-puzzolan cements manufactured from the clinker of high-lime Portland cement appear to give the most favorable results as far as strength and volume-constancy are concerned.

389. Uses. The relatively high workability, impermeability, and strength of Portland-puzzolan cement *in lean mixes* of concrete favor this cement for concrete in which strength is not a primary requirement, but, because of its relatively high shrinkage, this cement is unsuitable for rich mixes in thin sections subjected to prolonged drying. Portland-puzzolan cement of proper composition is suitable for mass concrete, hydraulic structures, and structures subjected to the action of sea and sulfate waters.

ALUMINA CEMENT

390. Alumina Cement. There has come into prominence in Europe a cement which has a high alumina content. It is made from a mixture of bauxite and limestone, which is fused in an electric furnace and the product ground. Under the commercial names of "ciment fondu," "ciment électrique," and "cilciment," it has been used for concrete in sea water and where a high strength is required at an early age, even though the cost is high compared with Portland cement. The alumina cements are not quick-setting but often attain strengths at 48 hours comparable to the 28-day strength of ordinary Portland cements. After 48 hours the strength increases much more slowly but continues to be about twice as great as the corresponding Portland cement strength. Tests have shown that the alumina cements resist the disintegrating action of sea water quite well. The analysis of *Lumnite*, an American alumina cement of this class, is shown below:

	Per Cent
Al_2O_3	40
CaO	40
Iron oxides	15
Silica, magnesium	5

Lumnite develops at 24 hours a somewhat greater strength than that of ordinary Portland cement at 28 days.

Considerable heat is developed as this cement sets, and care must be taken to prevent too rapid drying during this period.

OXYCHLORIDE CEMENTS

391. General. Oxychloride cements, commonly known as *Sorel cements*, are prepared by mixing either zinc chloride and zinc oxide or magnesium chloride and magnesia. The resulting oxychlorides of zinc and magnesium respectively form very hard cements. Magnesium oxychloride has a limited application as a structural cement in the manufacture of artificial stones, tiles, grindstones, and emery wheels. It is also used in flooring cements and stuccos.

392. Manufacture. Magnesium oxide for use in the manufacture of magnesium cements is prepared by burning magnesite in ordinary limekilns at a temperature of about 635° C. (1175° F.) for 24 hours. The kiln product is then ground to a fine powder and mixed dry with some inert material to be cemented, such as powdered quartz, marble, siliceous sand, or emery. The usual proportions of oxide are: for emery wheels, 10 to 15 per cent by weight; for strong building blocks, 5 to 10 per cent; and for common artificial stone, 3 to 5 per cent.

The dry ingredients, after mixing, are thoroughly dampened with magnesium chloride, passed through a pugging mill, and rammed into suitable molds.

Flooring cements, containing sawdust, wood flour, silica, talc, asbestos, pigments, etc., are prepared in a similar manner. A formula given by P. H. Bates for a top coat is as follows:

MATERIAL	PER CENT BY WEIGHT
Magnesia	45
Wood flour	15
Silica	15
Kaolin	10
Asbestos	5
Color	10
	100

A magnesium chloride solution of 22° Baumé gravity is added in proportions to give a desired consistency.

Magnesite stuccos generally contain magnesium oxide, ground silica, sand, and magnesium chloride.

393. Properties and Uses. The time of set of oxychloride cements depends on the proportioning and ingredients but is generally between 1 and 24 hours. Full strength is attained at 1 to 4 months. Grindstones and emery wheels prepared with this cement are aged at least 1 month before being put in service.

Artificial stones made with oxychloride cements will take a high polish and have high compressive strengths. The strengths of several such stones are shown in Table XXXVIII.

TABLE XXXVIII

Compressive Strength of Stones Made with Oxychloride Cement

Inert Material	Proportions by Weight of Magnesium Oxide, per cent	Age of Specimens, mo.	Compressive Strength, lb. per sq. in.
Pulverized quartz	12–15	12	7,270
Flour of emery	.....	24	19,640
Fine marble	15	36	11,560
Mill sweepings	12–13	9	6,130
Marble and sand	12	24	4,920
Coral sand	12	12	6,240

When used as flooring, only a wearing coat is ordinarily laid on concrete slabs, but on wood floors a binder course is poured with steel reinforcement and a wearing course is placed over this. The material is screeded to a depth ranging from 1/4 to 3/8 inch and troweled. Typical uses are as laboratory floors and railroad and subway car floors. This flooring withstands abrasion well but deteriorates when repeatedly wet.

QUESTIONS

1. Distinguish between hydrated and hydraulic lime.
2. Distinguish between the following cements: slag, natural, Portland, Portland-puzzolan, alumina, and magnesium oxychloride.
3. Define Portland cement, and state its approximate percentage composition.
4. What raw materials are mixed together to be calcined to form Portland cement?
5. Describe in detail the manufacture of Portland cement by the dry and wet processes. Compare the advantages of each.
6. Compare the characteristics of four major chemical compounds in Portland cement with respect to cementing value, rate of reaction, and amount of heat liberated.
7. Describe the chemical reactions which occur when water is added to Portland cement.
8. How is the time of setting of Portland cement controlled?
9. Describe briefly the gel theory of cement hardening.
10. How do the methods of manufacture of high-early-strength Portland cement differ from those of manufacturing standard Portland cement?

11. State the essential differences in composition and physical properties between standard Portland cement, high-early-strength Portland cement, and low- or moderate-heat-of-hardening Portland cement.

12. Distinguish between setting and hardening of cement.

13. State the A.S.T.M. specifications for the acceptance of Portland cement for time of set, tensile strength, and soundness.

14. Name three methods of determining the fineness of cement.

15. Name chemical compounds which may cause unsoundness in Portland cement.

16. Describe the essential features of the autoclave test of cement.

17. What causes volume changes in Portland cement mortar?

18. What are the effects of adding hydrated lime to Portland cement?

19. Discuss the general characteristics of Portland-puzzolan cement, alumina cement, and magnesium oxychloride flooring compound.

20. What type of cement would you select for the construction of a concrete pavement in an important street intersection? A sidewalk in a residential district? A floor of a subway car? A long-span concrete arch bridge? A large dam? A low-stressed foundation in dry location? A precast concrete pile for use in sea water? State your reasons in each case.

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SECTION 4

CONCRETE AND STONE

CHAPTER XVI

CONCRETE

Originally Written by Ralph G. Adams *

Rewritten by Lloyd F. Rader

394. Concrete as a Structural Material. Concrete is a mixture of inert materials of varying sizes which are bound together with a cement paste. A mixture of cement, water, and fine aggregate only is called *mortar*; *concrete* contains coarse aggregate in addition. The whole mass is deposited in a plastic condition and almost immediately a hardening process starts which, under proper curing conditions, may continue for years. Because it is placed in a plastic condition concrete lends itself successfully to all kinds of construction, the only drawback being that it must be confined in forms until a proper degree of hardening has taken place.

In structures and classes of work where tensile stresses are encountered, the concrete must be reinforced with steel. This leads to a complication of problems so far as design stresses are concerned, and hence only the fabrication and items affecting the concrete mixture will be discussed here.

The three principal factors which must be considered in casting a concrete structure are: the strength, durability, and economy desired. It is impossible in a general discussion to weigh the importance of these three items properly because many factors of design and economic conditions contribute to confuse the decision. For example, strength alone must not be sought wholly disregarding cost. A low cost factor, on the other hand, may make for low strength, poor quality, and a low degree of permanence of the structure. Again, durability and permanence may not be desirable if obsolescence and the consequent demolition of the structure are important considerations.

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* Assistant Professor of Testing Materials, Massachusetts Institute of Technology

These few examples show that the concrete mixture for any structure ought to be carefully designed and the various factors affecting its final properties controlled within reasonable limits. Uniformity of the hardened concrete is very essential so that whenever desired the same strength may be obtained in any portion of the structure.

CONCRETE MATERIALS

395. Cement. Portland cement should be specified for general concrete work and should conform to the standard specifications of the American Society for Testing Materials. Special cements may be specified for projects involving unusual requirements.

Storage of Cement. After delivery on the work the cement should be carefully stored in weathertight, but not airtight, buildings, the floors of which are raised from the ground. The storing should be done in such a manner as to permit of easy access for inspection and identification of each shipment.

Inspection and Testing. Each shipment of cement should be inspected by a competent inspector whose duty it is to select a sample for tests. The sample should be a fair average of a bag or barrel, and, if conditions permit, about 1 barrel in every 10 should be sampled. Usually tests are made on a mixture of the individual samples, but sometimes on important work the individual samples are tested separately.

For large and important operations, tests may be made on samples taken from segregated bins at the cement works, but the usual procedure is to test each shipment as it arrives on the job.

396. Water. There is usually very little trouble in obtaining suitable water for casting concrete. Either the city water supply is available or some proven source of drinking water is usually near at hand. Stagnant water from a small supply should not be used unless tested particularly for organic impurities. Sea water may be used in mixing mass concrete which has no steel reinforcement, although better concrete will be obtained with fresh water and this should be procured if at all available. Owing to the danger of corrosion, sea water should not be used in concrete which carries steel reinforcement.

397. Sand for Concrete Aggregate. *Granulometric Composition.* Investigations have shown that for the most part the sand should be coarse rather than fine. A sand showing proper gradation in size from fairly coarse to fairly fine is preferable to either a uniformly coarse or a uniformly fine sand. A rough empirical rule often applied requires that not more than 50 per cent of the sand shall pass a 30-mesh sieve and not more than 10 per cent shall pass a 100-mesh sieve.

A stricter rule for the gradation of a sand from coarse to fine sizes is as follows:

	Per Cent by Weight
Passing No. 4 sieve	Not more than 85
Passing No. 50 sieve	Not more than 30 Not less than 10
Removed by decantation	Not more than 3

These percentages are rather arbitrary and would have to be varied somewhat to suit local conditions. The gradation of sand is a question of economy, and too great a restriction cannot be laid upon it.

The term "fineness modulus" is often used to denoted the relative fineness of sand. Fineness modulus is defined as one one-hundredth of the sum of the cumulative percentages held on the standard sieves in a sieve test of a sand. Six sieves are used in the determination, Nos. 4, 8, 16, 30, 50, and 100, the clear opening of each sieve being one-half that of the preceding one. The smaller the value of the fineness modulus the finer is the sand. For a good grade of concrete sand the fineness modulus should be between 2,25 and 3.25.

Foreign Matter in Sand. If silt in the sand contains more than 10 per cent of organic matter, the latter constituting as much as 0.1 per cent of the sand, an appreciable injury results. Clay, if finely divided and uniformly distributed throughout the sand, appears to have little effect unless present in large amounts, perhaps 10 per cent or more. However, finishing of concrete floors, slabs, and pavements may tend to bring the fine material to the surface where it is easily worn away or scaled off. Specifications usually limit clay and silt in sand to 3 per cent by weight for important concrete work.

It is important, therefore, that the sand used on concrete work should be subjected to careful examination and tested systematically. It is not sufficient to specify that the sand be clean and sharp and accept it upon the basis of a casual inspection made by taking a bit between the fingers to establish its grittiness, and determining its cleanliness by the amount of discoloration produced by rubbing it in the palm of the hand. Presence of harmful matter can be determined by ignition of the silt, by a water wash test, or by the sodium hydroxide test.

The sodium hydroxide or *colorimetric* test is made as follows: A 12-ounce glass prescription bottle is filled to the 4½-ounce mark with the sand to be tested and a 3 per cent solution of sodium hydroxide is added until the total volume after shaking is 7 ounces. The bottle is stoppered, shaken thoroughly, allowed to stand for 24 hours, and the color of the solution noted. This color can be compared with standard color charts or with a standard solution of tannic acid and the relative amount of organic matter noted therefrom. In general, a color deeper than a light orange indicates an excess of harmful matter.

Loam or an excess of clay in sand is usually eliminated by washing, and a great deal of washed sand is used in concrete construction. Too much washing, however, tends to remove most of the fine particles and may cause the resulting concrete to be harsh and difficult to handle.

If the sand proves to have little or no harmful matter, its suitability for use with the coarse aggregate should be determined. Some form of mechanical analysis of both sand and stone should be applied. The sand should also be tested with cement for strength, usually in tension, to determine its value for use in the mortar. It is not necessary that the sand should be sharp.

Mica in Sand. The detrimental effect of the presence of even small percentages of mica, added to 1 : 3 mortars made with standard Ottawa sand, is shown in Fig. 101. This loss of strength, which is very considerable even if only a slight amount of mica is present, is due to two causes: first, because of its irregular shape the percentage of voids is increased; and, second, its smooth surface prevents proper bonding.

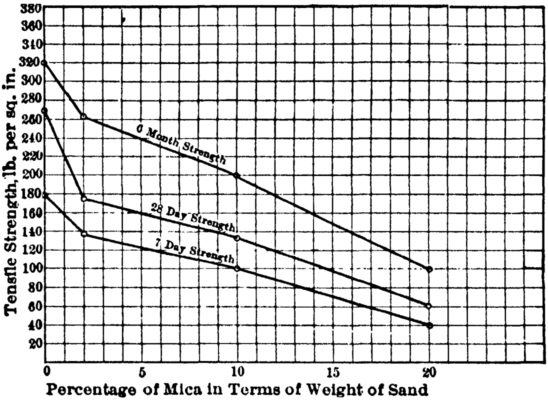

FIG. 101.—Effect of Mica in Sand on Tensile Strength of 1 : 3 Mortar.

Comparison with Standard Sand. Common practice in selecting sands for structural use is to prepare 1 : 3 mortar briquets of the commercial sand and of standard sand using the same cement for the two mixes, and to determine the percentage of the strength of the standard sand mortar developed by the unknown sand mortar at 7 and 28 days. Minimum allowable percentages of standard vary from 60 to 100 per cent, depending on the locality and the nature of the construction. This test is often applied to determine the strongest of a number of available sands.

398. The Coarse Aggregate. *Cleanliness.* All material under $\frac{1}{4}$ inch is commonly removed from either crushed stone or gravel, this fine part sometimes being suitable for use as sand. The usual requirement for clean gravel is that it be free from injurious amounts of coated particles, clay and silt, loam, alkali, and other deleterious substances. Shale particles, clay lumps, coal, chert, and soft fragments should not be permitted in appreciable quantities since they do not resist weathering. There is usually no trouble with the cleanliness of crushed stone if the parent rock is hard and clean.

Gradation. The maximum size of coarse aggregate allowable depends upon the nature of the work on which the concrete is used. For thin walls and sections the size should never exceed one-quarter of the thickness of the section. In reinforced-concrete work the maximum size is usually taken as three-quarters of the clear distance between reinforcing rods. For massive concrete, however, sizes up to 3 inches or larger may be used if special methods of puddling and tamping are adopted.

The coarse aggregate should be well graded from coarse to fine particles, and to determine this fact a standard set of sieves is often used. There are nine sieves in the set, namely: the 1½-inch, ¾-inch, and ⅜-inch sizes together with the standard set for the sand analysis, Nos. 4, 8, 16, 30, 50, and 100. As in the sand test, a fineness modulus for the coarse aggregate may be found. The value for an ordinary aggregate usually ranges between 5.5 and 7.5. Often a greater number of sieves are used in the larger sizes, i.e., 1½-inch, 1¼-inch, 1-inch, ¾-inch, ½-inch, ⅜-inch, and ¼-inch, and a graph is drawn plotting the cumulative percentages held on or passing each sieve against the size of the clear opening of the sieve. (See Fig. 102.)

Shape of Particles. From a standpoint of minimum void space, rounded stones are more desirable than irregular fragments; from the standpoint of ability to bond with the mortar, the rounded stones may be inferior, however, so that in general the shape of the particles will be found to be much less important than their size and hardness. Thin, flat pieces should be discarded. Large amounts of shale are particularly undesirable.

Gravel vs. Broken Stone. All stone should be examined for cleanliness and for the hardness and toughness of the rock particles. Either gravel or broken stone may be perfectly satisfactory, and neither can be said to be wholly superior to the other. If the consistency of the concrete is such as to constitute a rather dry mix, more tamping is necessary to obtain a dense concrete with broken stone than with gravel consisting of smoother and more rounded particles.

Gravel usually has a smaller percentage of voids than broken stone, and therefore a compact concrete may be secured with a somewhat smaller amount of mortar than would be required for broken stone.

On the other hand, if properly tamped, the broken stone will to some extent interlock, forming a dense and strong concrete, the same effect being possible with a well-puddled wet mix. Also, the rough surface of the broken stone usually results in developing a greater adhesive strength or bond between the stone and the mortar. This consideration cannot be taken to be universally applicable, however, for the adhesion of cement to stone is not wholly a matter of roughness or smoothness.

THE PROPORTIONING OF CONCRETE MIXTURES

399. Importance of Proper Proportioning. Upon important work, particularly if of large extent, a thorough study of the materials and the proper relative proportioning of those materials will generally produce better results both in decreased cost and in increased strength and durability of the final concrete. The cement is always the most expensive ingredient, and, therefore, if it is possible to reduce the amount of cement used by adjusting the proportions of the aggregate, producing thereby a leaner mix of equal or greater density and strength, economy is effected provided that the cost of handling this mix is no greater than that of a richer one.

400. Proportioning by Arbitrary Assignment. The oldest and probably the most popular method of proportioning is the arbitrary assignment of proportions of cement and of fine and coarse aggregate. This method has a basis of theory in the fact that for concrete of maximum density the voids in the coarse aggregate should be filled with mortar, in which the cement has filled the voids in the fine aggregate. In practice, however, the voids are never exactly filled, as an excess of mixing water and the entraining of air bubbles during mixing make further voids.

The voids in natural gravel usually run from about 30 to 40 per cent; in crushed stone they vary from 30 to 50 per cent, depending upon the shape and gradation in size of the particles. Because of the fact that when fine and coarse particles are mixed together, some of the fine ones are caught between coarser particles, the so-called expanded voids must be considered. Ordinarily 10 to 15 per cent is assumed as a value for these expanded voids. Hence arbitrary assignment commonly calls for a volume of fine aggregate equal at least to one-half the volume of the coarse material. For lean mixes a greater proportion of fine aggregate is necessary. The amount of cement required depends upon the use to which the concrete is to be put and the strength desired.

It is usually customary to state concrete proportions by volume, loosely measured, giving the number of parts of cement to parts of fine and coarse aggregate. It is impossible to state, arbitrarily, the proportions used in practice for concrete in any particular situation. The following mixes are given, however, as being fairly representative of practice and of conservative building code requirements:

1 : 1½ : 3 — a rich mixture used for columns and other structural parts subjected to high stresses or requiring watertightness and for structures exposed to severe weathering conditions.

1 : 2 : 3½—a standard mixture used for reinforced floors, beams, columns, arches, engine and machine foundations where vibration occurs, sewers, conduits, etc.

1 : 2½ : 4 — a medium mixture used for floors on the ground, ordinary machine foundations, retaining walls, abutments, piers, thin foundation walls, building walls, sidewalks, etc.

1 : 3 : 5 — a lean mixture for massive concrete, heavy walls, large foundations under steady load, stone masonry backing or filling, etc.

401. Proportioning by Mechanical Analysis. On important work a mechanical analysis of the aggregate is desirable since it affords a basis for determining the best proportions to be used with given materials, or for determining what size material should be added to the aggregate to make it more satisfactory in a concrete of given proportions. The least dense mixture of aggregate is made up of particles all of one size; the densest mix, of particles of graded sizes. A coarse aggregate of one size is preferable to a fine one, since there is less surface area to be coated with the cement. Fine aggregates are less dense and require more cement and water to coat their particle surfaces. This additional amount of paste still further reduces the density and increases the cost.

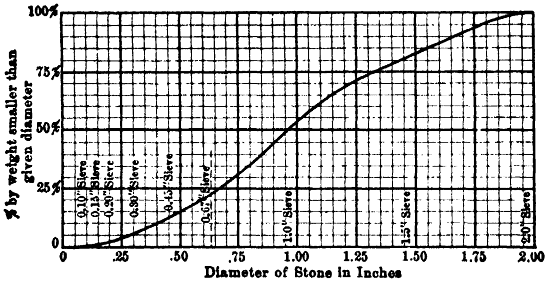

FIG. 102. — Typical Mechanical Analysis of Gravel.

The availability of an aggregate for a concrete mixture may be determined by a mechanical analysis of its particle sizes. This sieve analysis is obtained by screening a representative sample of the dry aggregate through a series of sieves with openings of decreasing size. The cumulative percentages held (or passing) each screen are an indication of the grading of the material. This is shown by plotting the cumulative percentage as an ordinate against the sieve opening as an abscissa (Fig. 102).

Feret and others have made careful study of the results of artificial mixes of aggregates. They proved, if aggregates were screened into three sizes, coarse, medium and fine, that the combination with greatest density was a mixture of 73 per cent coarse and 27 per cent fine with no medium at all. Greatest strength was given by nearly the same proportions, being 80 per cent coarse and 20 per cent fine aggregate. Stone of one size can be combined with finer stone or with a sand in accordance with these results.

Many "run of the bank" aggregates do contain medium-size material, which cannot be conveniently screened out. The densest mixture of such a material gives a gradation plot which appears to be a regular curve.

*Proportioning by Absolute Volume.** J. A. Kitts has successfully used a method of proportioning based upon the absolute volume of the materials. For this method the material, both coarse and fine, must be screened into separate sizes and recombined in exact proportions taking into account the specific gravity of the various materials. In order to make the method easy of application under job conditions he has devised different grading curves to suit varying conditions. Concrete proportioned and cast by this method is very dense, and the claims of economy of materials are substantiated by experience in many construction jobs both large and small.

402. Effect of Water. The arbitrary assignment of the mix and proportioning by mechanical analysis more or less assume that water is put into the mix for the purpose of producing a concrete which can be easily handled. In other words, if a more fluid mixture is desired more water is added. This procedure often leads to mixes which are much too wet, under which conditions the final concrete contains a large quantity of water voids, small in size but more or less connected together. These form passages through which surface water may seep and cause disintegration and spalling due to frost action and general weathering conditions.

Water reacts with the cement particles, causing chemical changes and combinations which result in the formation of the paste that binds the fine and coarse particles together. Considering the cement in the mix as the glue or binder for the inert particles, it is reasonable to assume that an excess of water produces a dilution of the glue and hence an inherent weakness in its bond strength.

A bag of cement requires about 2½ to 3 gallons of water to produce complete hydration and to carry along the chemical reactions. In a concrete mix anywhere from 5 to 12 gallons of water are added per bag of cement, depending upon conditions and the skill and knowledge of the operator. Some of this water is needed in the mix to wet the surfaces of the fine and coarse particles because the glue must have a consistency such that all cracks and minute irregularities will be completely filled

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* *Proc. Am. Conc. Inst.*, 1929.

Excess water acts as a lubricant in transporting the aggregate to the final place in the forms and is necessary to give proper workability, but a large excess of water tends to produce segregation of the aggregate particles from the paste and produces a mix which is harsh and non-uniform.

403. Workability and Consistency. The term *workability* as applied to concrete mixtures indicates the ease with which the mass of plastic material may be deposited in its final resting place in the forms without segregation or honeycomb to produce a uniform, homogeneous mass. The size and gradation of the aggregate, the amount of mixing water, the duration of mixing, and the size and shape of the forms are all factors of this vague and elusive term. No measure of workability has yet been devised which satisfactorily shows the ease or difficulty of placement of the concrete.

Consistency is generally considered descriptive of the apparent workability of the mix but it often falls far short of the actual conditions. The term consistency is descriptive of a particular condition of fluidity or lack of fluidity of any material and should always be qualified. Although several methods have been proposed for measuring the consistency of freshly mixed concrete, only two will be described, the slump-cone method and the flow table.

The slump cone is a metal form in the shape of a truncated cone, 12 inches high, 4 inches in diameter at the top and 8 inches at the bottom. The freshly mixed concrete is placed in the mold in 3 layers, each layer being puddled with 25 strokes using a 5/8-inch-diameter rammer. The form is immediately withdrawn, and the distance the mass of concrete subsides or "slumps" from the original 12-inch height is taken as a measure of the consistency of the mix. This test does not indicate the workability of the mix but for similar aggregate combinations it will show differences in water contents, mix, etc. The usual slumps for different classes of work are: roadways and heavy floors 1 inch to 3 inches; heavy beams and walls 3 inches to 6 inches; thin walls, columns, and ordinary beams 4 inches to 8 inches.

The flow table has been modified by various experimenters, but its fundamental feature is a table, 36 inches in diameter, mounted so that it rests on a cam. As the crank is turned the table drops suddenly 1/2 inch. A truncated metal cone, 5 inches high, 6 3/4 inches in diameter at the top and 10 inches at the bottom, is filled with concrete in two layers. Each layer is puddled as in the slump-cone test, the form is removed, and the table is jolted 15 times in about 10 seconds. The spread of the fresh concrete due to this treatment expressed as a percentage of the original bottom diameter of the cone is the "flow." The flow table is used mostly in the laboratory as a method of determining consistency and has not been used as a field method to any great extent.

404. Proportioning by Water-cement-ratio Method.* Duff A. Abrams has developed a method of proportioning concrete which is based on the amount of water used for making the mix. The term "water-cement ratio," as used by him, is the ratio of the volume of water to the volume of the cement. His tests tend to prove that the strongest concrete is that which requires the lowest water-cement ratio to give a required consistency of mix. The results of Abrams' tests are summarized in Fig. 103, which shows the relation between compressive strength of moist-cured 6-inch-diameter concrete cylinders, 12 inches high, at an age of 28 days, and the water-cement ratio of these concretes. The equation of the curve is $S = \frac{14,000}{7^x}$, where S = the compressive strength of the concrete in pounds per square inch and x = the water-cement ratio. The tests cover a wide range of mixes and consistencies except that results for dry consistencies were not included. For each mix, with the exception of neat cement, the maximum size of aggregates ranged from that passing a 1½-inch sieve down to that passing a No. 14 sieve.

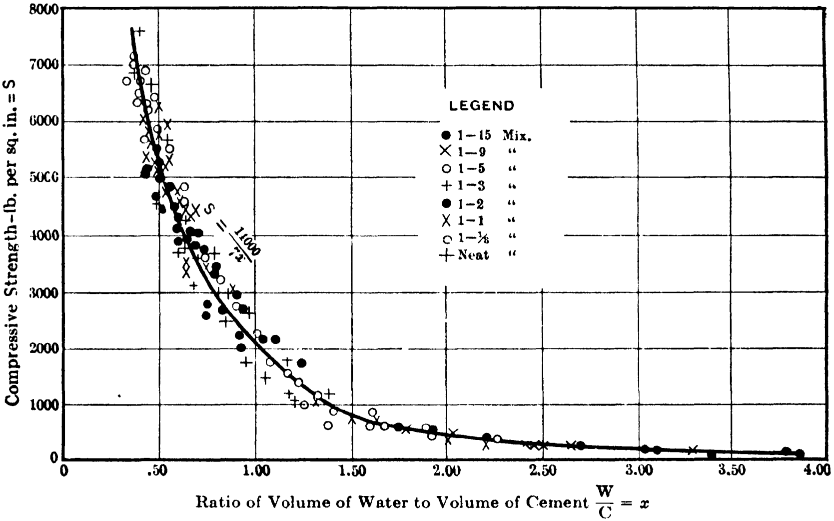

FIG. 103.—Water-cement Ratio Curve.

The fundamental water-cement ratio law may be stated as follows:

"For plastic mixes using sound aggregates, the strength and other desirable properties of concrete under given job conditions are governed by the net quantity of mixing water used per sack of cement." †

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* Design of Concrete Mixtures. *Structural Materials Research Laboratory, Lewis Institute, Bulletin* 1.

† Design and Control of Concrete Mixtures, Portland Cement Association, 3rd ed., 1929.

The method of proportioning based upon this law consists of selecting the water-cement ratio which will produce concrete of the desired strength and resistance to exposure and then determining the most suitable combination of aggregates which will give the necessary workability when mixed with cement and water in this ratio.

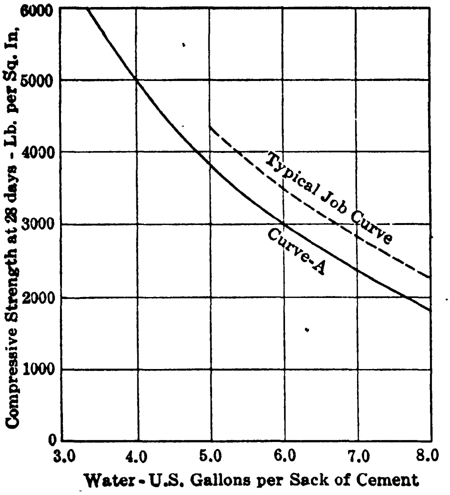

FIG. 104.—Relation between Compressive Strength and Water-cement Ratio.

In selecting the water-cement ratio, the strength requirements and the degree of exposure to which the concrete will be subjected should be carefully considered. The relation between compressive strength and water-cement ratio is shown by curve A in Fig. 104 and represents the *average* strength relationship for different brands of cement. Because different cements react differently when gauged with water and aggregate combinations are also very variable, the resultant strength for a given water content may be higher or lower than the indicated value from the curve.

For this reason some engineers in applying this method work out a job curve with varying water contents in combination with the aggregates and cement which are to be used. From this job curve the water content may be selected which will produce concrete of a desired strength.

For average conditions where there exists a fairly careful control of the measurement of the cement, water, etc., the strength of the resulting concrete is usually higher than that indicated on the average curve of Fig. 104.

Recommended water-cement ratios for various types of structures and degrees of exposure are given in Table XXXIX, which is taken from "Basic Principles of Concrete Making," by F. R. McMillan.

Trial-batch Method. The method of trial batches is extensively used in selecting the desired combination of aggregates which when added to the cement paste of given water-cement ratio will produce a concrete mixture of suitable consistency. The problem consists of obtaining a desirable balance between workability and economy. Size, grading, and surface characteristics of the fine and coarse aggregates, and the relative proportions of fine and coarse aggregates, are the factors of greatest

TABLE XXXIX

RECOMMENDED WATER-CEMENT RATIOS FOR CONCRETE TO MEET DIFFERENT DEGREES OF EXPOSURE

These requirements are predicated on the use of concrete mixtures in which the cement meets the present standard specifications of the A.S.T.M. and to which an early curing is given that will be equivalent to that obtained when protected from the loss of moisture for at least 10 days at a temperature of 70° F. Also that the concrete is of such consistency and is so placed that the space between the aggregate particles is completely filled with cement paste of the given water ratio.

Class of Structure Exposure	Water-cement Ratio, U. S. gal. per sack[1]		
	Reinforced Piles, Thin Walls, Light Structural Members	Reinforced Reservoirs, Water Tanks, Pressure Pipes, Sewers, Canal Linings, Dams of Thin Sections	Heavy Walls, Piers, Foundations, Dams of Heavy Sections
Extreme: 1. In severe climates as in northern U. S., exposure to alternate wetting and drying, freezing and thawing, as at the water line in hydraulic structures. 2. Exposure to sea and strong sulfate waters in both severe and moderate climates.	5½	5½	6
Severe: 3. In severe climates as in northern U.S., exposure to rain and snow, and freezing and thawing, but not continuously in contact with water. 4. In moderate climates as in southern U.S., exposure to alternate wetting and drying, as at water line in hydraulic structures.	6	6	6¾
Moderate: 5. In climates as in southern U. S., exposure to ordinary weather, but not continuously in contact with water. 6. Concrete completely submerged, but protected from freezing.	6¾	6	7½
Protected: 7. Ordinary inclosed structural members; concrete below the ground not subject to action of corrosive groundwaters or freezing and thawing.	7½	6	8¼

[1] Free water or moisture carried by the aggregate must be included as part of the mixing water.

importance in determining the combination which will give the necessary workability at the lowest cost.

The following procedure is typical of the trial-batch method of proportioning. The desired water-cement ratio is selected. A definite amount of cement is weighed and placed in the mixing pan, and the proper amount of water is added to produce a cement paste of desired water-cement ratio. Definite quantities of room-dry fine and coarse aggregates are weighed in suitable containers. Fine and coarse aggregates from the weighed quantities are added to the cement paste until a plastic mixture of desired consistency is obtained.

The remaining aggregate quantities are weighed and deducted from the original weights to determine the quantities used. The proportions by weight of cement to sand to coarse aggregate may be changed to volumetric proportions by dividing the weight of each material by its unit weight.

The slump-cone test is customarily used to determine the consistency. The following limits of consistency are recommended for various classes of concrete structures: *

Type of Structure	Slump in Inches	
	Minimum	Maximum
Massive sections, pavements and floors laid on ground...	1	4
Heavy slabs, beams, or walls...........................	3	6
Thin walls and columns, ordinary slabs or beams........	4	8

After a proportion has been established to give a certain consistency, further studies as to the ratio of fine to coarse aggregate may be made by mixing trial batches until a desirable combination is secured. Concrete mixtures having insufficient cement-sand mortar to fill the spaces between pebbles are difficult to work and result in rough, honeycombed surfaces. On the other hand, concrete mixtures in which there is an excess of cement-sand mortar will produce a low yield and the concrete is likely to be porous. A concrete mixture with proper amount of cement-sand mortar will have all spaces between pebbles filled with mortar after being lightly troweled.

Maximum yield is obtained by using a dense mixture of fine and coarse aggregates with as coarse grading and as stiff consistency as possible without producing harshness or stone pocketing. The yield of a trial batch may be determined by actual volumetric measurement or by adding the absolute volumes of the constituent materials. (See Art. 411.)

Proportioning by Trial Method on Job. The method of designing mixtures by trial may be applied on construction projects, using full-size

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* Design and Control of Concrete Mixtures, Portland Cement Association, 3rd. ed., 1929.

routine batches composed of stock aggregates which are usually damp. This application permits continuous control. The accuracy of the method is dependent upon the care with which the tests and observations are made. The amount of surface moisture on the aggregates, particularly sand, is determined by test. The amount of water to be measured into the batch of concrete is adjusted so that the proper water-cement ratio will be secured. The method is essentially a "cut-and-try" process. If the mixture is too wet, more aggregate may be added and a greater yield obtained. If the mix is too dry, yield must be correspondingly reduced. The correction for surface moisture on the aggregates must be recalculated for each change in the amount of aggregates.

405. Fineness-modulus Method. The fineness-modulus method of proportioning concrete has been advocated by Duff A. Abrams. It is based on the water-cement-ratio principle and on the assumption that the same amount of water is needed to wet the mixed aggregate to produce a certain consistency of concrete if the material has a given fineness modulus. (See Arts. 397 and 398.) This assumption is approximately true for mixed aggregates of about the same gradation and of equal fineness modulus, but does not hold for aggregates of different gradations even though of equal fineness modulus. Fineness modulus is a measure of relative fineness of aggregate and does not indicate gradation. Charts have been prepared showing the relations between fineness modulus of aggregate and compressive strength of concrete for mixtures of various water-cement ratios and consistencies as found by laboratory tests on aggregates of rather common gradations. These relations are of value but may not give desirable consistencies for aggregates of unusual grading. Abrams' original series of tests, although very complete and exact so far as the aggregates which he used were concerned, proved to be cumbersome and difficult to apply as a proportioning method under job conditions in general. The method has been largely supplanted by the trial-batch method of proportioning based on the water-cement-ratio principle.

Abrams has shown that, when the ratio of cement to aggregate is kept constant, the strength increases with the fineness modulus of the aggregate to a maximum (Fig. 105). Fineness moduli above this value mean that the material is too coarse for the cement paste to fill the voids. There is, then, a certain maximum fineness modulus for each mix and aggregate size beyond which value the aggregate should not be used. The maximum is higher for rich than for lean mixes. When aggregates are used where the largest size varies, with the same cement-aggregate ratio, the strength steadily increases with the fineness modulus, no maximum being reached (Fig. 106).

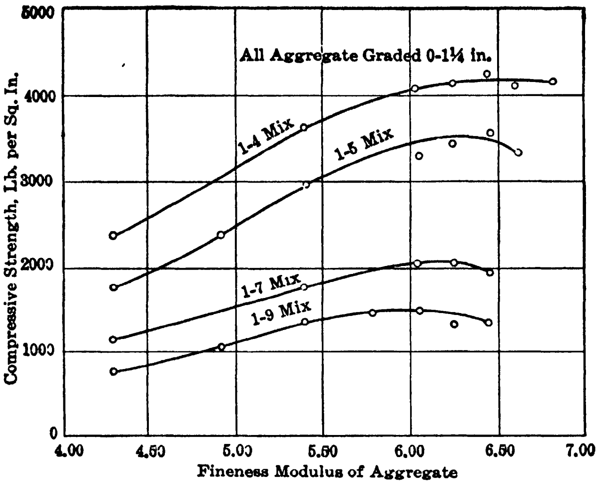

FIG. 105.—Relation between Fineness Modulus of Aggregate and Strength of Concrete.

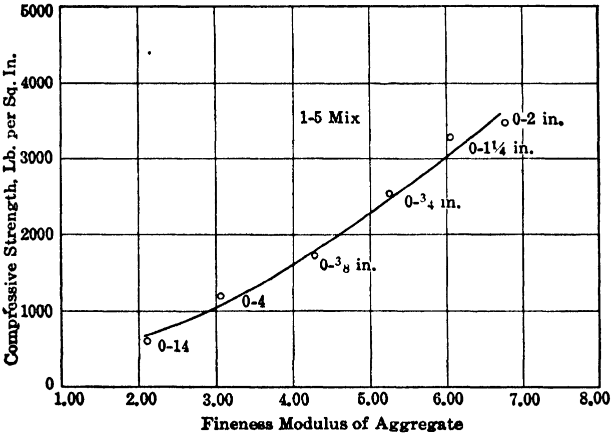

FIG. 106.—Relation between Fineness Modulus of Aggregate and Strength of Concrete.

406. Proportioning by Mortar-voids Method.* Professor A. N. Talbot has developed a method of proportioning concrete by the determination of voids in the mortar. The strength of concrete has been found to be dependent upon the composition of the cement paste which is assumed to occupy all the space in the concrete not filled with aggregate.

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* Talbot: Method of Proportioning by Voids in Mortar and Concrete, *University of Illinois, Engineering Experiment Station, Bulletin* 137.

The following symbols are employed:

a = absolute volume of sand in a unit volume of concrete in place.
b = absolute volume of coarse aggregate in a unit volume of concrete in place.
c = absolute volume of cement in a unit volume of concrete in place.
v = voids (air and water) in a unit volume of concrete.
$v + c$ = volume of cement paste in a unit volume of concrete.
$\frac{c}{v + c}$ = cement-space ratio, or proportion of cement in the cement paste.
a_m = absolute volume of sand in a unit volume of mortar.
c_m = absolute volume of cement in a unit volume of mortar.
v_m = voids (air and water) in a unit volume of mortar.
b_o = density, or absolute volume in a unit of bulk volume of coarse aggregate.

Typical relationships between compressive strength of concrete and cement-space ratio for different consistencies as determined by Talbot and Richart are shown in Fig. 107. The strength is less for the wetter consistencies. These strength values are lower than the average strengths for corresponding mixtures as reported by Abrams.

To design concrete of a given strength it is required to proportion the materials so as to give the proper cement-space ratio.

The consistency of the concrete is expressed in terms of the water content which produces the minimum voids in the mortar; this water content is called the *basic water content.* Fig. 108 shows values of voids in mortars corresponding to different water contents for a constant ratio of sand to cement. To be workable, mortars must have water contents equal to or greater than basic water content.

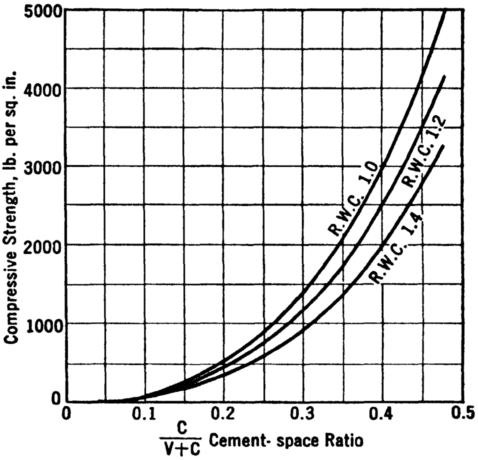

FIG. 107.—Relations between Compressive Strength of Concrete and Cement-space Ratio. (Talbot and Richart.)

Basic water content is determined experimentally in the laboratory for each proportion of sand to cement by a cut-and-try process. A cylindrical container of 200- to 300-cubic-centimeter capacity is suitable. A batch of sand and cement is weighed out and mixed dry. Water is added and the mortar is mixed and tamped into the container in a uniform manner. The net weight of the mortar placed in the container is obtained, and the volume of the original batch is calculated by a simple proportion. The factors for this water content can then be calculated. This process is continued until basic water content is determined.

In a similar manner the required factors are determined for mortars of different consistencies usually ranging from basic water content to 40 per cent above basic water content which is called 1.4 relative water content. This procedure is continued to obtain the required factors for a number of proportions of sand to cement. Characteristic curves can be plotted as illustrated in Fig. 109.

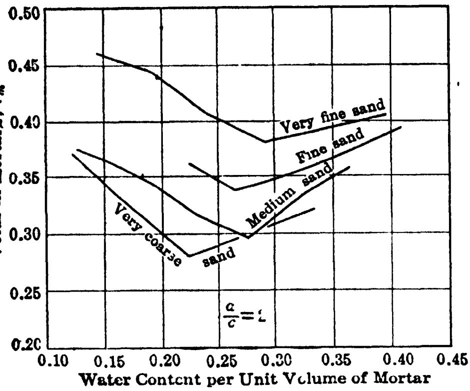

FIG. 108—Relation of Voids in Mortars to Water Content for $\frac{a}{c} = 2$.

The voids in the stone also are determined. A value of the volume of stone (b) can now be assumed. For example, if the voids in the stone equal 0.45, the absolute volume of the stone (b) cannot exceed 0.55 and, after the addition of mortar, will probably be less (0.50 to 0.45).

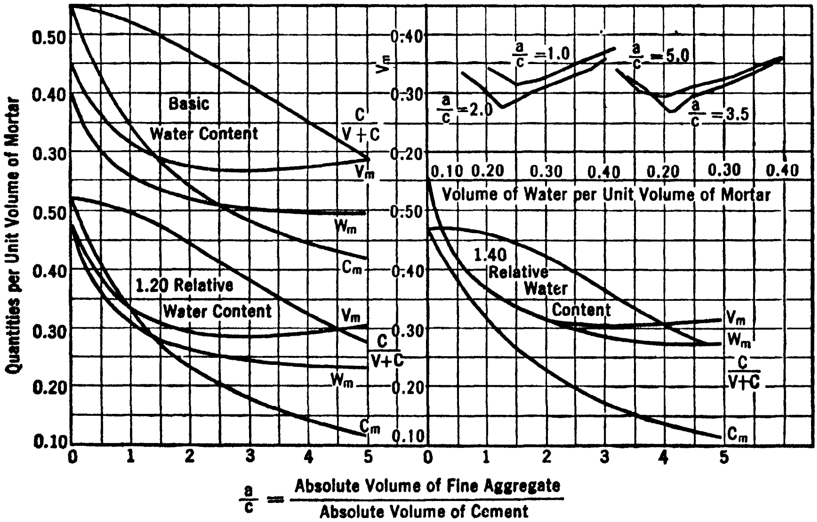

FIG. 109.—Characteristic Mortar-voids Curves. (Univ. of Ill., Eng. Exp. Sta., *Bull.* 137.)

Fig. 108 shows the effect of fineness of sand upon the mortar voids, v_m, for various water contents for a given ratio of sand to cement, and

Fig. 110 shows the effects of variations in consistency for various ratios of sand to cement $\left(\frac{a}{c}\right)$.

Illustration of Laboratory Determination of Mortar Voids. $a/c = 3.5$; absolute volume of sand = 210 cubic centimeters and of cement = 60 cubic centimeters; weight of sand = $210 \times 2.65 = 556.5$ grams and weight of cement = $60 \times 3.10 = 186$ grams; for 13 per cent of water use 96.5 grams water; net weight of mortar placed in container found to be 675 grams; capacity of container = 300.5 cubic centimeters; volume of batch =

$$\frac{(556.5 + 186 + 96.5) \times 300.5}{675} = 373.5 \text{ cc.}$$

$$a_m = \frac{210}{373.5} = 0.562 \quad \text{and} \quad c_m = \frac{60}{373.5} = 0.161$$

$$w_m = \text{water in mortar} = \frac{96.6}{374} = 0.258$$

$$v_m = 1 - (a_m + c_m) = 1 - (0.562 + 0.161) = 0.277$$

$$\frac{c}{v + c} = \frac{c_m}{v_m + c_m} = \frac{0.161}{0.277 + 0.161} = 0.366$$

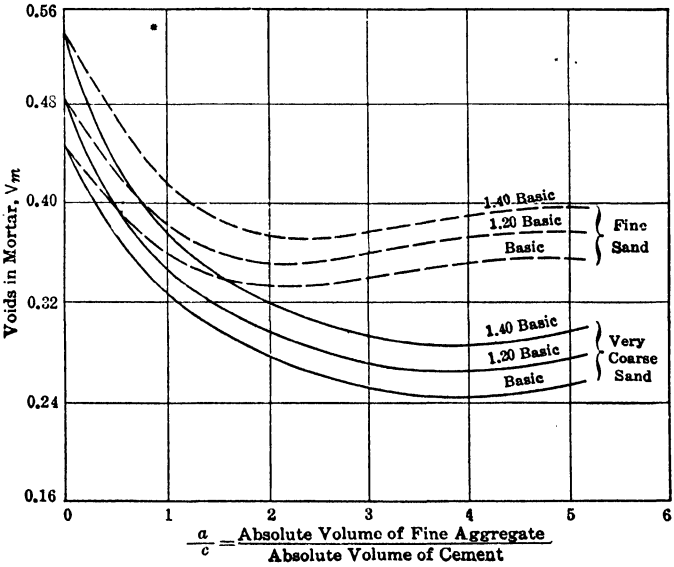

FIG. 110.—Characteristic Mortar-voids Curves at Three Water Contents.

This water content was found to give the minimum volume of mortar for this a/c ratio and is therefore the basic water content.

Example of Computation of Concrete Mixture. For compressive strength of 2200 pounds per square inch and consistency of 1.20 relative water content, find $c/v + c = 0.38$ from Fig. 107. From Fig. 109 for this cement-space ratio of 0.38, find $a/c = 3.0$; $v_m = 0.29$; $w_m = 0.24$.

Assume that crushed stone is to be used, for which b may be taken as 0.400.

$$v = v_m(1 - b) = 0.29(1 - 0.400) = 0.174$$

$$a + b + c + v = 1 \qquad (1)$$

$$a + 0.400 + c + 0.174 = 1$$

$$\frac{a}{c} = 3.0 \qquad (2)$$

Solving equations (1) and (2):

$$a = 0.320$$

and

$$c = 0.106$$

The proportion by absolute volumes is 0.106 : 0.320 : 0.400.

Material	Weight per Cubic Foot, pounds	Specific Gravity	Ratio of Absolute to Bulk Volume
Cement	94	3.10	0.485
Sand	110	2.65	0.664
Stone	104	2.70	0.616

The proportion by bulk volumes is

$$\frac{0.106}{0.485} = 0.218$$

$$\frac{0.320}{0.664} = 0.482$$

$$\frac{0.400}{0.616} = 0.649$$

$$1 : 2.21 : 2.98$$

Amount of mixing water $= w_m(1 - b) = 0.24(1 - 0.400) = 0.144$ cubic foot for 0.218 cubic foot of cement. The water-cement ratio is

$$\frac{0.144}{0.218} \times 7.5 = 4.95 \text{ gallons per sack}$$

This method of proportioning applies to dry as well as to plastic mixtures; when the voids in the concrete are completely filled with water as in plastic mixtures, the voids-cement ratio and the water-cement ratio are the same.

This method is scientific and is extensively used. The data obtained in the laboratory for given aggregates can be converted into field control charts for proportioning concrete.

407. Summary. All methods of proportioning which have been discussed have many valuable features regarding the economy of materials, the strength, and other desirable properties which a concrete structure should possess. The choice of a particular method is usually dependent upon the amount of field control which the engineer can employ in checking the different phases of the work. Care should be taken in combining different methods because sometimes this leads to impossible conditions of manipulation. For example, an arbitrary proportion can be adopted for any particular job and then, it being realized that the amount of water in the mix will affect the strength, a low water content may be chosen. This is as far as the choice of methods can be carried. The consistency of the resulting concrete is determined when the two quantities, mix and water content, have been decided upon.

The trend of specifications for concrete is towards the adoption of the following procedure: First, the choice of a water content which approximately determines the strength of the mix. Second, the determination of the quantities of fine and coarse aggregate by trial mixes varying the amounts to produce the desired workability. As a general rule the final quantities of fine and coarse aggregate are limited only by the requirement of producing a thoroughly workable concrete which does not segregate in transporting and placing. A further limitation, that the final volume of fine aggregate shall be not less than one-third nor more than one-half the total volume of the fine and coarse aggregates measured separately, is often imposed.

By this procedure, each job would require a different mix depending upon the particular conditions which have to be met, and the items of greatest density, gradation of material, and economy could be worked out by the engineer to suit the best interests of all concerned.

MEASUREMENT OF MATERIALS

408. Measurement of Cement. When cement is purchased in bags or sacks, its measurement is an easy matter. A sack when properly filled contains 94 pounds and is assumed to be 1 cubic foot in volume. A barrel of cement is equal to 4 sacks and weighs 376 pounds net. Bulk cement should be measured by weight because measurement by volume is unsatisfactory owing to the fact that a cubic foot of cement may be made to vary greatly in weight depending upon the amount of compaction.

409. Measurement of Water. Accurate measurement of water is important since water and cement constitute the cement paste which is the binding agent and has great influence on the strength and other properties of the resulting concrete. Volumetric measurement is usually employed on modern concrete mixers, the tanks being equipped with water gauges, meters, or adjustable discharge pipes so that the proper amount may be obtained for each batch. In stationary mixing plants, water is many times measured by weight. The amount of mixing water should be corrected for surface moisture in the aggregates, particularly in sand. The amount of moisture in the aggregate can be determined by weighing the aggregate before and after drying. The amount of surface moisture in sand can be determined by means of a Chapman flask according to A.S.T.M. Designation: C69-30.

410. Measurement of Aggregates. Volumetric measurement of aggregates is common but is likely to be inaccurate owing to different degrees of compaction and to bulking of damp aggregates, particularly sand. Sands containing moisture tend to occupy a greater space than dry sand when shoveled about, because the films of water adhering to the sand grains increase the resistance between the surfaces of the grains and tend to spread them apart. Therefore, a cubic foot of damp sand weighs less than a cubic foot of dry sand to which the same method of placement has been applied. This swelling tendency or bulking is greater in fine sands than in coarse and is greater with small percentages of water than with large. For a moderately damp (about 7 per cent water content) fine sand the bulking is about 25 per cent. Many methods of measuring sands to overcome this tendency have been investigated.

Measuring Sand by Inundation. The method of inundation gives nearly constant weights per cubic foot for sands of varying dampness. It is based on the principle that saturated sand has practically the same volume as dry sand. The method consists in sifting sand into a measure which contains a sufficient amount of water so that when the required volume is reached the surface of the sand is still below the surface of the water.

Measuring Aggregates by Weighing. In modern proportioning plants aggregates are weighed in order to eliminate the errors incurred in volumetric measurement. Correction for the weight of moisture in the aggregates should be made. Since most specifications are written for the materials to be measured on a volumetric basis, it is necessary to know the relationship between weight and volume in order to determine the proper weights of materials for a batch. The weight per cubic foot of dry aggregate may be determined by compacting the material in a container of definite size as specified by A.S.T.M. Designation: C29-27. Then the moisture in the aggregate in percentage by weight of dry aggregate should be determined. The weight of moist aggregate is equal to the sum of the weights of dry aggregate and moisture. Because of bulking, the weight of a cubic foot of moist aggregate will give a different result.

411. Quantities of Materials. In the estimation of the amounts of materials for a job, the cement factor, barrels per cubic yard of concrete, is usually obtained. This can be accurately determined by making use of the fact that the volume of concrete produced by a combination of materials is equal to the sum of the absolute volumes of the cement, the aggregate, and the water, provided that the concrete when placed has no void spaces. The absolute volume of loose material equals the unit weight of the material divided by the product of the apparent specific gravity of the material and the unit weight of water.

The principal salts encountered in alkali waters usually include: magnesium sulfate, calcium sulfate, and sodium sulfate, magnesium chloride, sodium chloride, and potassium chloride, together with carbonates of magnesium, sodium, and potassium. Of these the sulfates appear to be most active in causing disintegration of concrete; the chlorides also are active; the carbonates appear to be without effect.

From the physical point of view the action resembles the action of frost, except that it is more rapid. There exists, apparently, a disruptive force which destroys the bond and causes disintegration. This action appears to proceed most rapidly in the parts of a structure subjected to alternate wetting with alkali water and drying in the air. In porous concrete the action proceeds much more rapidly than in dense concrete.

The remedy, as for marine structures, lies in securing of the densest possible concrete, thus preventing injury by the exclusion of the salt-bearing waters.

434. Floor Hardening. Some concrete floors dust badly after the building is occupied. Other floors are not able to withstand heavy trucking. These faults can be laid to the mix, to excess of water, to lack of care in placing the concrete, or to quick drying out of the concrete. It is often possible to decrease the dusting or the wear by the application of a surface hardener. Various proprietary compounds are on the market. The usual types are magnesium fluosilicate, sodium silicate, zinc sulfate, linseed oil, wax, varnishes, or paints. Other methods that have been tried include alum, soap suds, and mixtures of fuel oil and soap. The Bureau of Standards has tested these types of hardeners by actual use on floors and by wear tests under office building conditions.

Magnesium fluosilicate, in solutions from 8 to 18 per cent, decreases dusting and wear, especially for the stronger solutions.

Sodium silicate, or water glass, gives excellent results, as do zinc sulfate and alum.

Linseed oil is a costly treatment, but effective.

Wax prevents dusting but does not harden the floor against wear. The varnishes and paints also prevent dusting but need renewal from time to time.

Soap or fuel oil and soap emulsions must be applied at regular intervals. The treatment gives the floor a polish and reduces dusting. Soap used alone has yielded the least satisfactory result.

435. Vacuum Concrete Process. Extraction of a large percentage of excess mixing water which is not needed for hydration of the cement but is necessary to secure plasticity of the concrete can be accomplished by subjecting the surface of freshly deposited concrete to a partial vacuum. Simultaneously with such extraction, the surface of the concrete is subjected to the pressure of the atmosphere which tends to consolidate the mass while in a plastic state, thus filling in void and air spaces left by the removal of water. The extraction of excess mixing water from the concrete lowers the water-cement ratio and consequently increases the compressive strength of the concrete. Shrinkage of concrete may be decreased by this treatment.

The excess mixing water is withdrawn through the agency of suction mats connected by suitable means to a vacuum pump. A mat consists of a tight, impermeable backing of rubber, wood, or metal, faced on the side toward the concrete with a filter fabric behind which are a series of channels through which the extracted water can flow to the suction outlet. With rigid forms, the necessary waterways are usually obtained by attaching a light expanded metal to the face of the form and then stretching the filter cloth over the expanded metal. For floors and pavements, flexible mats of sheet rubber about 3 feet by 10 feet in size are used with surface patterns on the lower side to provide waterways.

Fig. 115.—Vacuum Concrete Process Applied to Building Construction. (Courtesy of Vacuum Concrete Corp.)

The patterned surface of the rubber is covered with filter fabric which is cemented to the edges of the sheet. A band of plain rubber around the edges of the mat provides a seal and prevents air leakage. The vacuum pump is connected by light steel tubing or by rubber hose to a manifold which provides connections for several flexible hose lines leading to the suction mats. The hose lines are connected to outlet holes in the mats by suction cups. Fig. 115 shows the forms, hose lines, and connections for applying a partial vacuum to a concrete wall.

The concrete is mixed and poured in the usual manner. A vacuum of 20 to 25 inches of mercury is maintained for a period ranging from 4 to 30 minutes, depending upon the type and thickness of concrete, until the concrete has lost its plasticity. Owing to the partial vacuum produced under the mat, the surface of the concrete is subjected to compression by the pressure of the atmosphere on the outside of the mat. For flexible mats compression is about 1550 pounds per square foot for a mercury vacuum of 22 inches. The effect of this compression is to increase the density of the concrete, the voids left after extraction of the water being reduced in amount. It is possible to carry on this treatment without removing appreciable quantities of cement from the concrete. The concrete loses plasticity and becomes hard enough so that the mat and forms can be removed immediately after treatment.

The vacuum process of extracting excess mixing water has been used on concrete pavements, bridge decks, floor slabs, general concrete building construction, roofs, either precast or poured in place, and precast pipe and tile. The process has also been used in resurfacing concrete floors and pavements and in refacing walls. This treatment makes it possible to have lighter forms in construction and to strip the forms in a short time after pouring. Finishing operations may proceed immediately after treatment. The concrete should be adequately cured.

436. Architectural Concrete.* *Polished Surfaces.* Concrete with special aggregates in the surface may be polished by grinding stones to bring out the colors and designs in order to produce a pleasing ornamental effect. *Art marbles,* made of colored cements and crushed marble aggregates are used to imitate marble. Precast units of various shapes and color combinations may be molded using only a thin layer of special material and backing up with cheaper materials. After hardening, the concrete surface is ground to bring out the aggregate. *Terrazzo* is art marble molded in place in walls and particularly floors of public buildings. Special aggregates are rolled into the surface of the fresh concrete; after hardening the surface is ground smooth, exposing the aggregates which may be arranged to produce designs.

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* Concrete in Architecture, a bulletin published by the Portland Cement Association.

Ornamental Finishes. Ornamental finishes of elaborate design can be obtained by exposing special aggregates. A typical method is to lay out the designs by cutting them into plaster-of-Paris board; another plaster-of-Paris board is cast on top of the first one to give raised areas instead of recessed. Concrete composed of gray or colored cement and colored aggregates such as crushed marble and colored glass is poured in a thin layer on top of the second plaster-of-Paris board and is backed up with cheaper concrete. The forms are removed in a day or two and the aggregate is exposed by means of wire brushes. The units are then permitted to harden before being placed in the structure.

Stucco. Portland cement stucco is extensively used for exterior walls of buildings. The surface may be finished smooth or rough, and various patterns may be obtained by troweling, floating, rubbing, and sponging.

Painted Decorations. Interior concrete surfaces may be painted or stained to produce decorative effects. Care must be taken that the concrete is of uniform texture and free from surface defects and blemishes. The concrete should be moist cured for several days and then well dried out. Lime on the surface should be neutralized by application of a coat of aqueous solution of zinc sulfate. In a couple of days, a priming coat of boiled linseed oil should be applied to prevent the paint from penetrating too deeply. High-grade linseed oil paints or stains consisting of mixtures of China-wood oils and boiled linseed oils, thinned with turpentine and colored with pigments, have been applied satisfactorily. Designs may be stenciled on with paint. The painted surfaces should be protected by coats of clear varnish or shellac.

CONCRETE PRODUCTS

437. General. Building units of either plain or reinforced concrete are often poured and cured in plants devoted to the manufacture of such products, to be delivered when aged to the site of construction. Among these concrete products may be listed blocks, bricks, tiles, posts, sills, lintels, copings, etc. The most widely used of these are concrete building blocks and concrete bricks.

The building blocks are of varying shapes and sizes and are manufactured by the hand or machine molding of various mixes. The usual strength requirement for such blocks is an average compressive strength for 6 blocks of 1000 pounds per square inch of gross area, with no block below 700 pounds per square inch of gross area.

Concrete bricks are being used to a considerable extent; and if proper care is exercised in the selection of materials, in the manufacture, and in the curing, a medium-quality building brick can be produced. The properties and specifications for concrete bricks are included under the discussion of building bricks.

The absorption of concrete bricks is usually low, but the effect of repeated soaking and drying is to reduce the strength of the bricks considerably.

438. Curing of Concrete Products. Concrete products such as blocks, tiles, posts, etc., are often placed in a curing room immediately after fabrication to hasten the attainment of a reasonable strength. These curing methods consist of applying moist, warm air in "fog rooms" or "steam rooms." Steam, under a pressure higher than atmospheric, gives good results, as the higher temperature hastens the setting action and the moisture prevents any drying out. From a practical standpoint this process is often undesirable because of mechanical difficulties encountered with maintenance of the necessary steamtight chamber. Experiments with 1 : 2 : 4 concrete have shown that steam pressures up to 165 pounds per square inch are beneficial. A normally cured concrete gave a compressive strength at 28 days of 2300 pounds per square inch. The same strength was obtained with the same concrete when 36 hours old, after it had been cured for 12 hours in steam at 165 pounds per square inch pressure (366° F.). A strength of over 4000 pounds per square inch was developed by concrete which had been 40 hours in the steam chamber. These tests show a slow increase in strength for the concrete after its removal from the steam.

PHYSICAL PROPERTIES OF CONCRETE

439. Compressive Strength. The compressive strength of concrete is dependent primarily on the water-cement ratio. Other factors such as character of the cement, conditions of mixing, deposition, curing and aging, character and grading of the aggregates, and size and shape of test specimen have a bearing on the compressive strength.

Effect of Character of the Cement. All Portland cements behave similarly, but they do not gain their strength at the same rate. This is brought out in Fig. 116, which shows tests of concrete made from 32 brands of cement which were conducted in the Portland Cement Association laboratory. In this diagram, which represents age-strength relation, are shown two of the highest, two of the lowest, and the average of the 32. The shaded area represents a belt 10 per cent above and 10 per cent below the average curve. The numbers in the circles at each of the five ages represent the number of cements which fall within the band 10 per cent above or below the average, also the number which fall outside of that band on both sides.

Effects of Variations in Mix and Consistency. Fig. 117 shows that the water-cement ratio fixes the compressive strength, regardless of variations in the cement content or in consistency.

Effects of Curing and Aging. Curing and aging cannot be separated; an increase in age provides for further chemical combinations if the conditions are favorable for continued reaction Fig 117 shows the effect of age on the water-cement ratio compressive strength relation for moist-cured concrete. The similarity in the curves for the various ages should be noted.

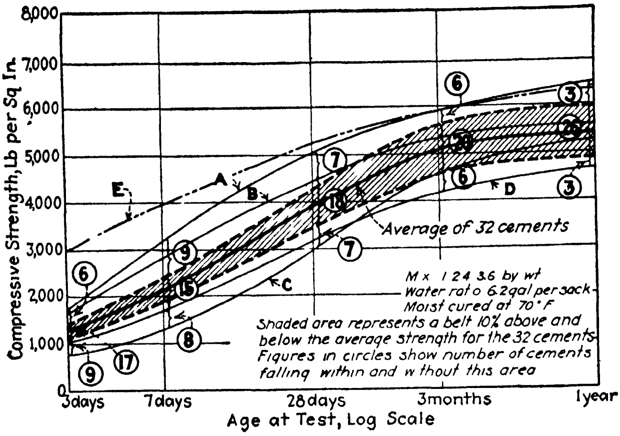

FIG 116—Age *vs.* Compressive Strength of Concrete for 32 Standard Portland Cements (Courtesy of F R McMillan)

Mix 1 2 4 3 6 by weight water cement ratio 6 2 gal per sack moist room curing

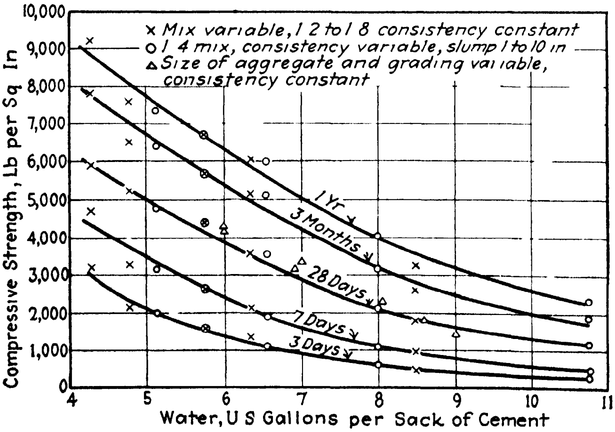

FIG. 117—Compressive Strength of Concrete of Varying Water Contents at Different Ages (Courtesy of F R McMillan)

Moist room curing, 6 by 12 in cylinders

Effects of Variations in Size and Grading of Aggregate. For ordinary size ranges, size of aggregate has no appreciable effect on the strength of concrete. The grading of the aggregate has much less effect on the water-cement ratio compressive strength relation than is commonly believed. When the differences in the amount of water required for aggregates of different gradations are compared on the basis of water-cement ratios, the differences in strength due to grading are not important. These points are illustrated in Fig. 117.

Effect of Shape of Test Specimen. Compression tests of concrete are ordinarily conducted on cylindrical specimens with height equal to twice the diameter so that surfaces of rupture produced upon fracture will not intersect the end bearings. Tests conducted on short cylinders or prisms will give greater strengths than those obtained on cylinders of standard height. The ends of the cylinders should be carefully formed to give parallel, smooth surfaces so as to obtain uniform distribution of stress. A uniformly stressed cylinder which has been properly molded will break in the shape of a double cone with vertex in the center of the cylinder.

Effect of Size of Test Specimen. The effect of size of test specimen upon compressive strength of concrete as determined by R. F. Blanks and C. C. McNamara * is given in Table XL. It is customary to state compressive strength in terms of the values obtained on 6-inch by 12-inch cylinders.

TABLE XL

RELATION BETWEEN SIZE OF SPECIMEN AND COMPRESSIVE STRENGTH OF CONCRETE

Diameter of Cylinder, inches	Height of Cylinder, inches	Per Cent of Compressive Strength of 6-in. by 12-in. Cylinder
2	4	108
3	6	106.5
4	8	104
6	12	100
8	16	96
12	24	92
18	36	86
24	48	84
36	72	83.5

440. Tensile Strength. In Fig. 118 are shown the results of tensile tests of concrete at various ages plotted in terms of the water-cement ratio. The same characteristics of the water-cement ratio strength rela-

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* *Proc. Am. Conc. Inst.*, v. 31, 1935.

tion will be noted for tensile as for compressive strength. The tensile strength of ordinary concrete ranges from about 7 to 10 per cent of the compressive strength.

The tensile strength of concrete is a property of limited importance because, the tensile strength being low in comparison with the compressive strength, concrete is very seldom designed to withstand tensile stresses. It will usually be found to be more economical to use steel reinforcement than to depend upon the tensile strength of concrete.

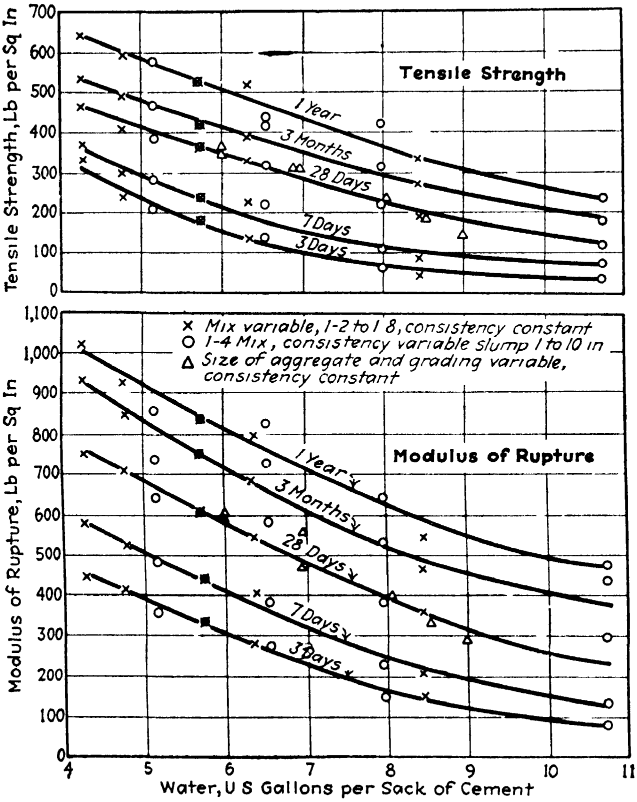

FIG. 118—Tensile and Flexural Strengths of Concrete of Varying Water Contents at Different Ages (Courtesy of F R McMillan)

Moist room curing, tension cylinders, 6 by 18 in, beams, 7 by 10 by 38 in

441. Flexural Strength. The flexural strength of plain concrete is almost wholly dependent upon the tensile strength. Experiments show, however, that the modulus of rupture is considerably greater than the strength in tension. Results of flexural tests of concrete at various ages plotted in terms of the water-cement ratio are given in Fig. 118. The same general characteristics of the water-cement ratio strength relation are shown in these results as for compressive strength. Flexural strength is of importance in the design of concrete pavements.

Fig. 119 shows the results of tests made by Abrams and reported in the *Proceedings of the American Concrete Institute*, 1922.

442. Shearing Strength. The shearing strength of concrete is a most important property of the material, since it is the real determining factor in the compressive strength of short columns. The strength of concrete beams is also, under certain conditions, dependent upon the shearing strength of the material.

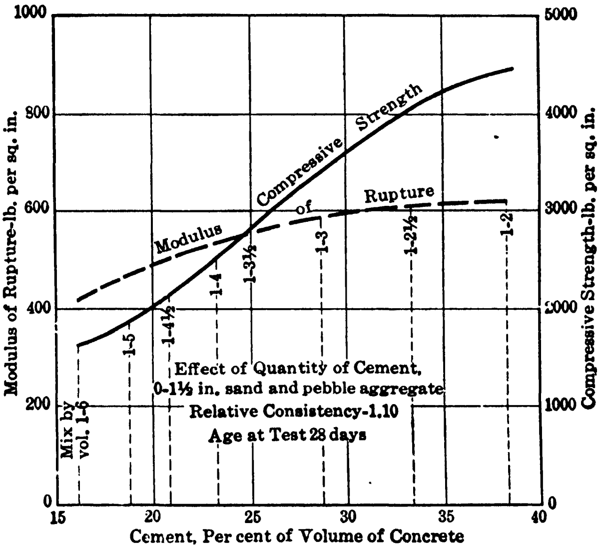

FIG. 119.—Effect of Quantity of Cement on Flexural and Compressive Strength of Concrete.

The average strength of concrete in direct shear varies from about one-half of the compressive strength for rich mixtures to about 0.8 of the compressive strength for lean mixtures.*

443. Elastic Properties. The elastic properties of concrete are of importance not only because of their bearing upon the deformation of concrete structures under load, but also because in the design of reinforced concrete it is necessary to know the relative stresses in the steel and the concrete under like distortions.

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* University of Illinois, Engineering Experiment Station. *Bulletin* 8.

Fig. 120 shows typical stress-strain diagrams for short prisms of concrete in compression.

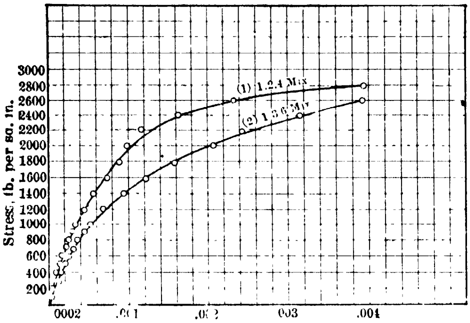

Fig. 120.—Stress-strain Diagram for Concrete in Compression. Age 3 Months.

Concrete is not perfectly elastic for any range of loading, an appreciable permanent set taking place for even very low loads, and the deformation is not proportional to the stress at any stage of the loading.

There can be, therefore, no elastic limit for concrete in the true sense of the term. There appears to be a stress, however, below which repetition of the same load does not cause appreciable increase in set, while beyond this stress repetition of load causes increased set indefinitely, finally resulting in rupture far below the normal ultimate strength. For practical purposes, therefore, it is convenient to consider this stress as the elastic limit. Experiments made by Bach, Probst, Van Ornum, and others seem to place this stress at about 50 to 60 per cent of the ultimate strength.

The elastic properties of concrete vary with the richness of the mixture and with the intensity of stress. They also vary with the age of the concrete.

444. Modulus of Elasticity. Since the deformation of concrete is not proportional to the stress at any stage of the loading, the modulus of elasticity is not a constant for any appreciable range of stress, decreasing as the load increases. The modulus of elasticity is customarily determined by one of three arbitrary methods: (1) the initial tangent method, in which a tangent is drawn to the curve at its origin; (2) the tangent method, in which a tangent is drawn to the curve at a point corresponding to a given stress; and (3) the secant method, in which a line is drawn through the origin and a point on the curve corresponding to a given design stress, as for example 800 pounds per square inch. The slope of the line gives the value of the modulus of elasticity in pounds per square inch.

The initial tangent modulus is of little value except for comparing the stiffness of rich and lean concretes. The tangent modulus and particularly the secant modulus are of importance for reinforced-concrete design. Values of the tangent and secant moduli vary ordinarily from 1,000,000 to 5,000,000 pounds per square inch dependent upon the method used. The modulus is higher for richer mixtures and increases with the age of the concrete.

445. Ratio $\frac{E_c}{E_s}$. The relative moduli of elasticity of concrete and steel determine the relative stresses in the two materials when the combined concrete and steel member is deformed a given amount. So long as the bond is not destroyed, the ratio $\frac{E_c}{E_s}$ fixes the relative stresses in the concrete and steel. E_c for concrete of 2000-pounds-per-square-inch compressive strength is about 2,000,000 pounds per square inch, and for steel E_s is about 30,000,000 pounds per square inch. The value of the ratio $\frac{E_c}{E_s}$ is, therefore, about 1/15.

446. Stress-strain Curves. Bach determined the true elastic curve in compression by repeatedly loading and unloading the test specimen to a given stress until the set at zero load became constant. At low stresses, the required constant set is soon obtained, but as the stresses are increased, the number of times the specimen must be loaded is correspondingly greater. The elastic deformation for a given stress is determined by subtracting the permanent set from the total deformation. The true elastic curve is obtained from a number of elastic deformations corresponding to different values of stress. The true elastic curve is useful in determining the change of shape of concrete after removal of stress, but does not indicate the total amount of deformation which the material undergoes for a given stress. The total-deformation curve is of importance in reinforced-concrete design, since the unit stress carried by the steel is a function of the total deformation of the combination of steel and concrete.

Bach determined the equation for unit deformation in compression of true elastic curves to be of the exponential form,

$$\epsilon = KS_c^m$$

where $K = \frac{1}{E_c}$, m is a constant varying from 1.11 to 1.16, and S_c is the compressive stress. Bach determined the modulus of elasticity in compression, E_c, from the true elastic curve using the tangent method.

The curves of Fig. 120 are typical stress-total deformation curves for concrete in compression. These curves have often been found to approximate closely to parabolas, the axis of which is vertical, the origin being located at the point representing the ultimate strength.

This fact has been made the basis of some methods of concrete beam design wherein the variation in stress in the concrete is assumed to be parabolic from the neutral axis to the extreme fiber. This means that the design is really based upon the ultimate strength of the material. This method has been replaced to a great extent by methods which assume the stress-strain curve to be a straight line for stresses under the allowable working stress. The computations required are thus simplified, and the design is based upon safe working stresses instead of the ultimate strength of the material.

447. Fatigue of Concrete. Plain concrete, when subjected to flexure, exhibits fatigue. The flexure-resisting ability of a concrete of a given quality is indicated by an endurance limit whose value is dependent upon the number of repetitions of stress. The Illinois Division of Highways found that an endurance limit of 50 per cent of the flexural stress which would cause rupture (known as the modulus of rupture) permitted indefinite repetitions of load without failure. In concrete pavement design, the allowable flexural working stress is limited to 50 per cent of the modulus of rupture strength of the concrete used so that the pavement will be able safely to resist stresses which will be periodically repeated a great many times during the life of the pavement.

448. Adhesion to Steel. The adhesion of concrete to steel is chiefly important in its bearing on the design of reinforced concrete. The bond strength is dependent principally upon the richness of the mix and the character of surface of the steel. Table XLI based upon tests made at the University of Illinois gives representative values of the bond between concrete and steel rods.

TABLE XLI

ADHESION OF CONCRETE TO STEEL RODS

Mix	Steel Rods			Adhesive Strength, lb. per sq. in.
	Kind	Size, inches	Depth Imbedded, inches	
1 : 2 : 4	Plain round..........	½ and ⅝	6	438
1 : 2 : 4	Plain round..........	½ and ⅝	12	409
1 : 3 : 5½	Plain round..........	½ and ⅝	6	364
1 : 3 : 5½	Plain round..........	½ and ⅝	12	388
1 : 3 : 5½	Cold-rolled shafting...	1 and ½	6	146
1 : 3 : 5½	Mild steel flat........	$\frac{3}{16} \times 1\frac{1}{2}$	6	125
1 : 3 : 6	Tool steel round......	¾	6	147

The adhesive strength of 1 : 2 : 4 concrete to plain round rods appears to be about 400 pounds per square inch. In situations where a higher bond strength is required, it is customary to secure a mechanical bond by means of some form of deformed bar.

C. A. Menzel reported in 1939 the following conclusions as a result of research on pull-out tests, involving 1-inch round and square bars cast in concrete prisms:

> Transverse lugs are more efficient on deformed bars than longitudinal lugs.
>
> The resistance of deformed bars has more relation to concrete compressive strength than that of plain bars.
>
> Bond is increased by sandblasting the steel bars.
>
> Modern steel bars of ordinary manufacture are smoother than those of 20 years ago.
>
> Slip is greatly increased as steel stresses are raised.
>
> Bond is better with dry than with wet mixes of concrete.

449. Protection of Steel from Corrosion. Experience, gained at the time of the demolition of reinforced-concrete structures after years of exposure in damp situations, and carefully conducted experiments have shown that concrete forms a most effective preventive of the corrosion of steel imbedded therein. Particularly is this true if the concrete is mixed sufficiently wet so that the steel is completely covered by a wash of thin grout.

Experiments made by Professor Charles L. Norton for the Insurance Engineering Station in Boston led to the following conclusions:

> Neat Portland cement, even in thin layers, is an effective preventive of rusting.
>
> Concretes, to be effective in preventing rust, must be dense and without voids or cracks. They should be mixed quite wet where applied to the metal.
>
> The corrosion found in cinder concrete is mainly due to the iron oxide, or rust, in the cinders, and not to the sulfur.
>
> Cinder concrete, if free from voids and well rammed when wet, is about as effective as stone concrete in protecting steel.

450. Contraction and Expansion. The coefficient of expansion of 1 : 2 : 4 concrete has been determined by several investigators with considerable uniformity to be about 0.0000099 per degree Centigrade (0.0000055 per degree F.). This value differs so slightly from the coefficient of expansion of steel that there is little danger of failure of the bond of concrete and steel in reinforced concrete by reason of temperature changes.

In addition to the volumetric changes due to temperature variation, concrete is subject to other volume changes caused, as in mortars (Art. 383), by the chemical processes of setting and hardening or by variation in the moisture content. Experiments made to determine the expansion and contraction of concrete while hardening are not numerous, but they show conclusively that concrete hardened in air contracts, and concrete hardened in water expands, the amount of change in volume being dependent upon the richness of the mixture. Experiments made by White (Art. 383) indicate that the expansion or contraction even of old concrete, when alternately wet and dried, is far from being negligible. Pieces of concrete, presumably not leaner than 1 : 3 : 6 or richer than 1 : 2 : 4, sawn from a sidewalk after 20 years in service, showed an expansion of 0.05 and 0.06 per cent when placed in water, and the same contraction when subsequently allowed to dry in air.

If this concrete were restrained so that no volume change could take place, the resultant stresses introduced, considering the modulus of elasticity of the cement to be 2,000,000 pounds per square inch, would amount to 1000 to 1200 pounds per square inch, a stress probably equal to at least half the ultimate strength if in compression, and far exceeding the ultimate strength if in tension.

451. Plastic Flow. Plastic flow, or time-yield, of concrete is the deformation that occurs under sustained stress. This phenomenon of flow is also called creep. Plastic flow is considered to be due largely to the seepage of water from the gel when an external load is applied to the concrete. The flow of water to or from the cement gel takes place through minute capillary channels which permeate the mass. The flow along the capillaries is a function of the pressure gradient along these channels. The greater the compressive stress, the steeper the pressure gradient and the more rapid the expulsion of water. The rate of expulsion is also a function of the vapor pressure on the outside of the mass. Shrinkage due to loss of moisture and time-yield due to seepage are interrelated phenomena, although they may be conveniently considered as separate and additive in their effect.

A portion of the total yielding may be due to crystalline flow which in metals is called creep and to viscous flow which refers to movement of particles one over the other, as in the flow of oil. Davis * suggests that differences in flow observed in concrete containing different mineral aggregates may be due to crystalline flow, and that the existence of lateral flow accompanying axial flow when the lateral dimensions are unrestrained may be caused by viscous flow.

Davis found that, the higher the sustained stress, the greater the flow. The moisture content of the cement gel has a marked effect upon the time-yield, the flow of a totally dry concrete being of small magnitude. The extent of hydration of the cement alters the time *vs.* flow relation appreciably, since concrete of greater age under given curing conditions at the time of loading shows less plastic flow. In plain concretes flow has been observed to continue even after almost 7 years under sustained stress, although the rate of flow is very small at such ages. Usually the flow practically ceases after 1 or 2 years.

Small plain concrete cylinders stored in dry air under sustained stresses within the range of ordinary working stresses for concrete may

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* R. E. Davis, H. E. Davis, and J. S. Hamilton: Plastic Flow of Concrete under Sustained Stress, *Proc. Am. Soc. Test Mats.*, v. 34, Part II, 1934, pp. 354-386.

have a total change in length due to flow and shrinkage combined equivalent to 1 or 2 inches per 100 feet in 7 years. For cylinders stored under moist conditions, the total deformation due to flow and expansion may be only one-fourth to one-third of the total deformation of similar concretes stored in dry air.

After release of sustained load, a recovery takes place which may continue over a period of several weeks and which may reach an appreciable fraction of the flow produced by the previously sustained load. This recovery is probably due to reversal of the seepage and to the resilience of the compressed aggregate particles.

Davis found the total unit time-deformations of air-stored reinforced columns to be from one-third to one-half of those in corresponding air-stored plain concrete columns. These deformations cause appreciable changes in the distribution of stress between the steel and concrete in reinforced-concrete columns under load in dry air, the stress in the steel being increased. The use of at least a medium grade of reinforcing steel for concrete compression members and of coatings on the surface of the concrete which prevent the loss of moisture may be warranted sometimes as a means of preventing excessive stresses in the steel. In general the results of tests indicate that plastic flow does not seriously reduce the strength of most reinforced-concrete structures.

452. Weight of Concrete. The weight of concrete is a factor in design, as it must be included in the dead load on any structure. The weight is dependent almost entirely upon the character of the aggregate and the density of the concrete. If the aggregate, both fine and coarse, is of well-graded stone and sand, and the concrete deposited in a manner to insure the minimum of void space, the weight may run as high as 160 pounds per cubic foot, and for less carefully chosen materials or less perfectly executed work the weight may not exceed 140 pounds per cubic foot. For practical purposes of design it is customary to assume the weight of stone concrete to be 150 pounds per cubic foot. The weight of cinder concrete varies from 110 to 115 pounds per cubic foot.

453. Fire-resistant Properties. Concrete as a fire resistant has been subjected to various experimental trials; but the best proof of its value lies in the experience afforded by many very severe fires wherein concrete well demonstrated its superiority over most other materials which are used for fire protection.

The value of concrete as a protection for steelwork in case of fire is due to several considerations. In the first place, concrete is in itself incombustible; second, its temperature coefficient is practically the same as that of steel, thus giving it an advantage over materials like terra cotta, which expands much more rapidly than steel, and hence tends to fail by reason of the destruction of the bond caused by unequal expansion; and third, the rate of heat conductivity of concrete is very low, owing in part to its porosity and consequent air content, and in part to the dehydration of the water of chemical combination, the volatilization of which absorbs heat. This latter action increases the porosity, and hence the conductivity of the concrete which has suffered dehydration is still further lowered, and the penetration of the dehydrating action proceeds very slowly.

The concrete which thus becomes dehydrated is seriously injured, but the effect is seldom appreciable to a depth of more than a fraction of an inch, except in very hot and long-burning fires. Concrete called "cinder concrete," in which the usual coarse stone aggregate has been replaced by cinders, has been found quite as effective a fire resistant as stone concrete.

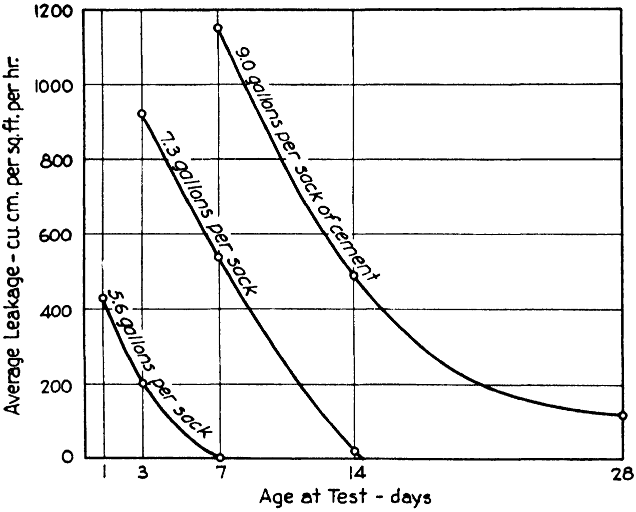

FIG. 121.—Effect of Water Content and Curing on the Permeability of Concrete. (Courtesy of F. R. McMillan.)

In general it is considered that a covering of concrete over steelwork, 2 inches in thickness, is sufficient to protect the steel effectually against temperatures sufficiently high to cause warping and twisting, with consequent failure of the structure.

Fire tests on concrete columns by the Bureau of Standards have shown that spalling of the concrete varies with different aggregates. Limestone, traprock and blast-furnace slag resist particularly well, while quartz gravels cause the greatest spalling. Quartz and granites have a sudden expansion of considerable magnitude at a temperature of 575° C. (1067° F.).

454. Permeability Tests. Fig. 121 gives the results of permeability tests on mortar disks, 6 inches in diameter by 1 inch thick, the specimens being subjected to a water pressure of 20 pounds per square inch for 48 hours after different periods of moist curing at 21° C. (70° F.). These results show that leakage at a given age can be reduced by using mixtures of low water-cement ratio and that, for a given water-cement ratio, the permeability can be decreased to a low value by extending curing.

QUESTIONS

1. State the characteristics of good fine aggregate for concrete.

2. Show how the results of a mechanical analysis of aggregate may be expressed graphically.

3. Name several examples of foreign matter in sand, and state why each is undesirable.

4. Define fineness modulus of aggregate and give typical values for fine and coarse aggregates for concrete.

5. State approximate specific-gravity values and percentage of voids for concrete aggregates.

6. State the principle of the water-cement-ratio method of proportioning concrete mixtures, and describe how the principle could be applied in proportioning concrete for a given job. Sketch the general shape of compressive strength *vs.* water-cement-ratio curve.

7. Compare the basic theory and the adaptability to field practice of each of the following methods of proportioning concrete:

(*a*) Proportioning by mechanical analysis.

(*b*) Water-cement-ratio principle (trial-batch method).

(*c*) Water-cement-ratio principle (including the use of the fineness modulus).

(*d*) Proportioning by mortar voids.

8. Define with respect to concrete: workability, consistency, basic water content, yield, density, bulking, permeability, durability, plastic flow.

9. State the advantages and disadvantages of three methods of measuring sand for concrete.

10. State the type of vibrating equipment you would select for the following concreting operations: (*a*) a concrete pavement, (*b*) a reinforced-concrete beam, (*c*) a concrete dam, (*d*) a reinforced-concrete pipe 12 inches in diameter, and (*e*) a high wall for a bridge abutment.

11. Describe two methods of depositing concrete under water.

12. Describe the precautions you would employ in pouring a reinforced-concrete building in freezing weather.

13. Discuss the importance of curing concrete. Describe four field methods of curing concrete pavements.

14. Discuss the relationship between combined water and curing.

15. Describe four methods of waterproofing concrete.

16. What effect has sea water upon concrete, and how may such effect be minimized?

17. Describe the essential features of the vacuum concrete process.

18. Distinguish between the following terms relating to concrete: (*a*) art marbles, (*b*) terrazzo, (*c*) stucco, and (*d*) ornamental finishes.

19. The proportions of a Portland cement concrete mixture are 1 : 2.0 : 3.1 by volume. The water-cement ratio is 6.5 gallons per sack of cement. The slump was 3 inches. The materials have the following properties:

	Specific Gravity	Unit Weight, pounds per cubic foot
Cement	3.1	94
Sand	2.65	105
Stone	2.80	104

Calculate the yield of concrete per sack of cement, the cement factor in barrels of cement per cubic yard of concrete, the quantities of materials required per cubic yard of concrete, and the weight of the concrete per cubic foot.

20. Solve problem 19 for a Portland cement concrete mixture composed of the same materials having proportions of 1 : 1.5 : 2.5. The water-cement ratio is 5.0 gallons per sack of cement. The slump was 2 inches.

21. Write a full discussion of the elastic properties of concrete as expressed by the modulus of elasticity. Include the following points:

(*a*) Shape of the stress-strain curve.

(*b*) Initial tangent *vs.* tangent *vs.* secant modulus.

(*c*) Values of unit stress for which modulus is commonly determined.

(*d*) Effect of mix, age, and curing on the value of the modulus.

(*e*) Name a value of the modulus commonly used in designing reinforced-concrete beams.

22. A concrete mixture was tested in compression after curing for 1 day in air and 27 days in water. The cylindrical specimen was 6 inches in diameter and 12 inches high. An ultimate compressive stress of 4160 pounds per square inch was obtained. The following data were obtained by means of a compressometer which had a distance between gauge points of 8 inches:

Load on Cylinder, pounds	Left Gauge, inches	Right Gauge, inches
500	0.0200	0.0200
5,300	0.0201	0.0202
9,710	0.0203	0.0204
15,150	0.0207	0.0206
19,800	0.0213	0.0206
24,870	0.0219	0.0206
29,230	0.0223	0.0208
32,640	0.0226	0.0209
36,450	0.0230	0.0210
39,690	0.0232	0.0212
42,840	0.0235	0.0214
46,800	0.0236	0.0219
50,870	0.0241	0.0220

Draw the stress-strain curve, and determine the modulus of elasticity by the secant method for a design stress of 800 pounds per square inch.

23. A high-early-strength Portland cement concrete mixture was tested in compression after curing 1 day in air and 6 days in water. The cylindrical specimen was 6 inches in diameter and 12 inches high. The proportions of the mixture were 1 : 2.0 : 3.1 by volume, and the water-cement ratio was 6.5 gallons per sack of cement. The ultimate compressive stress was 4730 pounds per square inch. The following data were obtained by means of a compressometer which had a distance between gauge points of 8 inches:

Load on Cylinder, pounds	Left Gauge, inches	Right Gauge, inches
330	0.0200	0.0200
3,880	0.0204	0.0200
8,980	0.0207	0.0200
13,340	0.0211	0.0203
18,950	0.0212	0.0205
23,690	0.0214	0.0209
27,830	0.0218	0.0209
33,400	0.0221	0.0213
38,200	0.0224	0.0217
40,620	0.0225	0.0219
44,570	0.0228	0.0220
48,770	0.0231	0.0224
52,710	0.0233	0.0228
56,590	0.0235	0.0230
59,970	0.0237	0.0233

Draw the stress-strain curve, and determine the modulus of elasticity by the secant method for a design stress of 800 pounds per square inch.

24. Calculate the modulus of rupture of a concrete beam, 6 inches by 6 inches in cross-section, tested on a 24-inch span under center loading. The mixture is described in problem 19. The breaking load was 3960 pounds. What would be the allowable flexural working stress for this concrete for pavement design?

25. Calculate the modulus of rupture of a concrete beam 8 inches by 8 inches in cross-section, tested on a 30-inch span. The load was applied at the third points of the span. The breaking load registered on the testing machine was 8200 pounds.

26. Discuss the effectiveness of concrete as a fire-resistant material for construction.

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CHAPTER XVII

BUILDING STONES, STONE MASONRY, AND ROAD METAL

ORIGINALLY WRITTEN BY IRVING H. COWDREY[*]

REVISED BY LLOYD F. RADER

BUILDING STONES

455. Stone as a Structural Material. The term "building stone" is applied to all those classes of natural rock which are employed in masonry construction. Stones form, with the exception of timber, the only important class of materials that may without alteration of their natural state be used directly in the construction of engineering works.

Aside from purely structural uses, great quantities of stone are utilized on other kinds of engineering construction, such as for flagging and curbing, for paving blocks, and as crushed stone for road building, railroad ballast, and concrete aggregate.

456. Classification of Rocks. *Geological Classification.* In the usual geological classification rocks are divided into *igneous rocks* formed by consolidation from a fused or semi-fused condition; *sedimentary rocks,* formed by the solidification of material transported and deposited by water; and *metamorphic rocks,* which are formed by the gradual change of the structure and character of igneous or sedimentary rocks through the agency of heat, water, pressure, etc. Granite, greenstone, basalt, and lava are common examples of igneous rocks; sandstone, limestone and shale, of sedimentary rocks; gneiss, marble, and slate, of metamorphic rocks.

The geological classification has only a limited bearing upon the consideration of rocks as building stones. Igneous rocks are usually nonlaminated and more or less crystalline in structure; sedimentary rocks are distinctly stratified, having, therefore, original cleavage planes; metamorphic rocks may or may not be laminated, depending upon the pressure encountered during metamorphism. Most of the metamorphic rocks which have been changed largely through the agency of pressure, water, and heat are crystalline in structure.

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Physical Classification. † With respect to the structural character of large masses, rocks are divided into *stratified* and *unstratified.* The structure of unstratified rocks is, for the most part, an aggregate of crystalline grains firmly adhering together. Granite, trap, basalt, and lava are examples of this class.

Stratified rocks may be divided into the following classes according to physical structure:

Compact crystalline structure (marble).
Slaty structure (shale, slate).
Granular crystalline structure (gneiss, sandstone).
Compact granular structure (blue limestone).
Porous granular structure (minute shells cemented together).
Conglomerate (fragments of one stone imbedded in mass of another).

457. Granite. Granite is the term applied to a plutonic,* igneous rock, the structure of which varies from finely granular to coarsely crystalline. Its principal mineral constituents are quartz and feldspar, with varying amounts of mica, hornblende, etc. Its prevailing color is gray, though greenish, yellowish pink, and red shades are found.

Granite is more extensively used as a building stone than igneous rock of any other class. It works with difficulty, owing to its hardness and toughness, but its quarrying is usually facilitated by the existence of planes of weakness: the *rift,* extending either in vertical or horizontal planes; and secondary planes, the *grain,* along which the rock may be less readily split, at right angles to the rift. As a rule the quarry rock shows joints or fissures in the direction of the rift, and often a secondary series of joints exists in the direction of the grain. The removal of rectangular blocks of large or small dimensions is thus facilitated.

Granite is used for foundations, base courses, columns, and steps in building construction, and is suitable for any situation where strength or hardness is required. It is used to a limited extent as an ornamental stone, its suitability being dependent upon color and texture.

458. Gneiss. Gneiss has the same composition as granite, which it resembles in appearance, but differs in physical structure, the various constituents being arranged in more or less parallel bands. The rock therefore splits readily into flat slabs, which renders quarrying less expensive than that of granite and makes the stone valuable for foundation

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* I. O. Baker: "Masonry Construction." Baker uses the term "stratified" in a broad sense to include both bedded sedimentary and banded metamorphic rocks.

† Plutonic rocks are igneous rocks formed by the solidification of molten material prior to its emergence on the earth's surface; volcanic rocks have cooled on the earth's surface

walls, street paving, curbing, and flagging. It is found in the same general localities as granite.

459. Limestones. The term limestone is commonly applied to all stones which, though differing from one another in color, texture, structure, and origin, possess in common the property of containing carbonate of lime (calcite) or calcite and the double carbonate of lime and magnesia (dolomite) as the essential constituent. In addition they contain as impurities oxides of iron, silica, clay, bituminous matter, talc, etc. Different limestones may be listed according to structure, composition, and mode of origin under the following heads:

Crystalline Limestone or Marble. The term "marble" is commonly applied to any limestone that will take a good polish. It is properly applied only to those limestones which have been exposed to metamorphic action and rendered more crystalline in structure.

The structure of marbles varies from finely to coarsely crystalline. Marbles are found in almost every conceivable color, and are often richly streaked with several colors. All varieties of marble work well, the finer-grained white marble being especially adapted to carving. Marble has been used in this country principally for interior decoration, but many varieties are entirely suitable for exterior construction. Most of the colored, mottled, and veined marbles are imported into this country. Quantities of white and black marbles are quarried, however, in Vermont, Georgia, New York, Pennsylvania, Maryland, and California. Some beautiful colored and mottled marbles are obtained from Tennessee and Vermont.

Compact Common Limestones. These are usually very fine-grained limestones of varying textures and colors, giving rise to many varieties. The best known and most widely used American limestone is the *Bedford limestone,* also called "Indiana limestone." This is a fine-grained, oölitic limestone which is made up of small rounded concretionary grains cemented together by carbonate of lime. It is quarried in the Bedford-Bloomington district in Indiana. Geologically it is known as the Salem limestone. It is found in two general color classifications, gray and buff. Deposits of light gray stone are the most abundant and have been the most used. The stone can be worked with remarkable ease and hardens on exposure. The rock has little tendency to split along bedding planes. It has been extensively used for the exterior construction of buildings, for bridge piers, and for heavy cut-stone masonry in general. A similar stone is quarried at Bowling Green, Kentucky.

"Travertine" is a compact fine-grained limestone deposited on the surface by running streams and springs. The term "onyx" or "onyx marble" is often applied both to travertine and to stalactite and stalagmite, which are deposits of limestone, often beautifully banded and streaked with colors, formed on the roofs, walls, and floors of caves.

Onyx marbles (using the term in the sense above mentioned) differ from marbles of the common type only in that they are purely chemical deposits rather than products of metamorphism from preëxisting calcareous sediments. The travertine varieties are products of deposition from hot springs carrying lime carbonate in solution, together with small quantities of iron and manganese carbonates and other more rarely encountered constituents. The stalactite and stalagmite varieties differ only in manner of formation, being cold-water depositions made on the roofs, walls, and floors of limestone caves. Both varieties owe their banded structure and variegated colors to the intermittent deposition and the varying content of impurities like the metallic oxides.

The onyx marbles are considered the most beautiful of decorative stones. They cut readily and take a high finish, and are largely used for interior decorations.

A large part of the onyx marble used in the United States is imported from Mexico. There are, however, important quarries in Arizona and California. The foreign onyx comes largely from Algeria and Italy.

460. Sandstones. "Sandstones are composed of rounded and angular grains of sand so cemented and compacted as to form a solid rock. The cementing material may be either silica, carbonate of lime, an iron oxide, or clayey matter." *

Sandstones vary greatly in color, hardness, and durability, but include many of the most valuable varieties of building stone for exterior construction. The qualities of sandstone as a structural material depend largely upon the character of the cementing material, the sand grains being very nearly a pure quartz for all. If the cement is siliceous, the stone is light-colored, hard, and sometimes difficult to work, but very durable. If iron oxides comprise the greater part of the cementing material, the color is a red or brownish tone and the stone usually is not too hard to work well, though it does not always prove very durable. If the cementing material is lime carbonate, the stone is light-colored, soft, and easy to work, but less durable than either of the above varieties. Clayey sandstones are the poorest class. They are soft and easily cut, but are particularly subject to the disintegration caused by weathering because of their high absorption. Some sandstones contain very little cementing material, but owe their strength largely to the pressure under which they have been solidified. Such stones are a light gray color, work easily, and, if they possess sufficient cohesive strength, are very durable. Sandstones containing varying amounts of grains of feldspar or mica are inferior to ones the grains of which are entirely quartz. The following are the principal well-known sandstones in this country:

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* Merrill: "Stones for Building and Decoration," p. 299.

The *brownstones* of Connecticut, Massachusetts, Pennsylvania, New Jersey, North Carolina, and a few other localities are handsome, dark, reddish-brown stones, fine-grained, easy to work, and capable of taking a good "rubbed" finish. With the exception of the Massachusetts stone, they occur in distinctly laminated beds and must be used on their natural beds. These stones, having iron oxides for a great part of their cementing material, are usually subject to the disintegrating effect of atmospheric agencies and therefore do not usually rank especially high in durability.

The *Ohio stone*, *Berea sandstone*, or *Amherst stone* is a fine-grained, light buff, gray, or blue-gray stone having silica for the most part as its cementing material, the amount of cement being low. These stones cut and work readily, are well adapted to carving and, when those portions containing iron pyrites are excluded, are very durable. The principal quarries are located at Amherst and Berea, Ohio, and the stone has been largely used in the cities of the Middle West.

The *Waverly stone* is a fine-grained homogeneous stone of a light drab or dove color, quarried only in the vicinity of Cincinnati, Ohio. It is sometimes called the *Euclid bluestone*. It resembles the Ohio stone except that it has a finer and more compact texture. It works easily and, except for portions containing iron sulfides, is a handsome and durable stone.

The *Potsdam red sandstone* from Potsdam, New York, is composed wholly of quartz grains cemented by a small amount of silica with just enough iron oxide to give it a reddish or brownish-red color. It is fine-grained, handsome in appearance, works well though rather hard, and is the strongest and most durable of sandstones after becoming hardened by seasoning.

The *Lake Superior stone* is a Potsdam stone of medium fineness. It has a light red-brown color and is often spotted gray. It is quarried largely at Marquette, Michigan. This stone resembles the Potsdam stone of New York, except that it has rather more cementing material and therefore is not quite as hard and strong. It works well and is very durable.

The *Medina sandstone* of western New York is a hard, moderately fine-grained stone, either red or gray in color. The red variety resembles the Potsdam stone, except that it is not so fine in texture, and is similarly used. The gray variety is rather too hard to work for general building purposes, but is largely used for street paving and curbing, where it has the advantage of some other hard stones, like granite or trap, in that it does not wear smooth.

The *Rocky Mountain sandstones* include many varieties of excellent building stone. The best-known ones are very fine-grained, soft-textured stones of a dark brown color. They work well, take a good "rubbed" finish, and are fairly durable.

✓**461. Slates.** Ordinary slate is a siliceous clay, compacted and more or less metamorphosed after deposition as fine silt on ancient sea bottoms. The pressure due to thousands of feet of overlying material is largely responsible for the solidification of the clay into rock having very marked cleavage planes. The most valuable characteristic of slate is its pronounced tendency to split into thin sheets having smooth regular surfaces. The non-absorptiveness of slate, its great toughness and mechanical strength, and its non-conductiveness for electric currents are other valuable attributes.

462. Traprock. This term has no strict geological interpretation. It is used primarily by engineers and is commonly understood to embrace all dark, fine-grained igneous rocks which show no free silica in the form of quartz crystals. In consequence of this definition, it properly includes basalt, fine-grained diorite and gabbro, and many of the felsites. Very frequently other rocks, like dark fine-grained sandstones, porphories, syenites, and even some dense shales and dolomites, have properties such that they are marketed and accepted under the broad characterization of "traprock."

463. Dimension Stone. Building stone reduced to blocks of definite shapes and sizes for structural uses is commonly referred to as "dimension stone." Dimension stone for construction of building walls may be cut stone or ashlar. Cut stone blocks are cut or finished accurately to definite shape and size, many times to meet the dimensions given in detailed drawings. The blocks may be rectangular or specially shaped for cornices, corners, caps, etc. The setting of cut stone requires great care. Relatively small rectangular blocks having sawed or rock-face surfaces are called "ashlar." A wall built of ashlar blocks of various sizes with non-uniformly spaced joints is termed "random ashlar."

464. Production of Dimension Stone. The production of two widely used structural building stones, granite and Bedford limestone, will be described. The methods of quarrying and milling granite are typical of the processes employed for hard stone while the methods for Bedford limestone are typical for relatively soft stone.

✓*Quarrying of Granite.* Drills are required to cut granite since it is so hard. Either compressed-air hammer drills or, occasionally, steam-driven or air-driven reciprocating drills are used. Drill bits range from about 1 to 3 inches in diameter, a change to a smaller size bit being made about every 4 feet of depth. Holes are drilled 15 to 20 feet deep. A thin passageway is cut through the webs between drill holes by means of rectangular drill bars called "broaching tools." The granite is fractured into large blocks by means of blasting powder.

Small blocks are obtained by plug-and-feathers wedging. "Feathers" are iron strips curved on one side to fit the drill hole and flat on the other.

Two feathers are placed in a drill hole and a"plug" or iron wedge is hammered between them. Blocks of stone are lifted out of the quarry by derricks.

Milling of Granite. Milling processes for cutting and finishing granite blocks are carried on by machine or by hand. Machine processes consist of sawing, polishing, sand blasting, and pneumatic surfacing. Granite is sawed either by gang saws or by rotary saws. Gang saws consist of a number of steel blades set parallel to each other in a frame which is drawn back and forth either in a straight line or in with a swinging motion. The blades are about ½ inch thick and have notches in the bottom edge for holding abrasive steel shot. Granite is cut into blocks or slabs by gang saws; additional cutting such as cutting the ends of blocks is done by rotary saws, 7 to 12 feet in diameter, which have detachable steel teeth. Abrasive steel shot is fed to the blade. Abrasive circular saws up to 30 inches in diameter are used for making cuts of small depth and for edging, jointing, chamfering, etc.

Machine polishing is carried on in three stages: rough grinding, fine grinding, and glossing. Rough grinding is done with steel shot or coarse silicon carbide under ironing wheels up to 6 feet in diameter and 3000 pounds in weight which are rotated on a horizontal surface of the granite. Fine grinding is carried on by means of a wheel, with emery or fine silicon carbide as abrasive, and glossing is done by a buffing wheel with putty powder. Special silicon carbide wheels are used for cutting and polishing special shapes. Granite columns are cut by turning lathes and then polished smooth.

The sand-blast process drives white silica sand as abrasive at a high velocity through a hand-controlled nozzle against the stone surface. For carving ornaments or lettering, the face is covered with a rubberlike protective coating in which a stencil of the design is cut out, leaving only those parts of the granite exposed which are to be etched. This is a very effective and economical process for etching surface ornament, relief carving, and lettering, and also for cleaning and finishing sawed surfaces.

Pneumatic surfacing machines are used for roughing, pointing, and bushing plane or flatly curved surfaces. Pneumatic tools guided by hand are employed in finishing practically every bush-hammered surface of any considerable area from rough or sawed surfaces.

Hand work is required in general for molded work, surfaces below a projection, heads, internal angles, sinkages, joints, and practically all irregular pattern stones. Hand cutting tools comprise chisels, chippers, points, plug drills, hand hammers, peen hammers, bull set hammers, bush hammers, wedges and shims, etc. Cutting granite by hammering on a tool is in reality a crushing process since the minerals of the stone are broken into small pieces or formed into dust.

Surface Finishes of Granite. "Polished" finish has a mirror gloss and brings out the full crystalline pattern and color. It is used for store fronts, base courses, monuments, thin facing, and veneer. "Honed" finish has a dull gloss without reflections, is free from scratches, and gives softer color effects than polishing. A "rubbed" surface is smooth without gloss. "Hammered" surfaces obtained by means of bush hammers may be coarse hammered using a four-cut bush hammer, medium hammered using a six-cut bush hammer, or fine hammered using an eight-cut bush hammer. This finish shows parallel ridges, is light in tone, and is suitable for general building work. "Pointed" finish is a roughly indented finish with fairly uniform texture, the size of point used and the density of distribution of indentations determining the grade: coarse, medium, or fine. It gives rugged texture effects and is economical for large surfaces. "Peen-hammered" surface is a very coarse, axed finish less regular than four-cut and has rugged texture effects. "Rock face" is rough split face with edges pitched to an approximate plane.

FIG. 122.—Electrically Operated Channeling Machines in Operation in a Bedford Limestone Quarry in Indiana. (Rader.)

Quarrying of Bedford Limestone. Stripping of clay overburden and removal of poor grade rock are preliminary operations in Indiana limestone quarries in Lawrence and Monroe Counties. Since Bedford limestone is relatively soft, blocks can be cut out by means of a "channeling" machine which has a reciprocating cutting tool composed of three to five sharpened steel bars. Channeling machines, operated either electrically or by steam power, are run back and forth on a track cutting either one or two channels in the rock. (See Fig. 122.) Blocks about 4 feet wide and

10 feet deep are cut the length of a quarry and then are broken loose from the floor by drilling and wedging using "plug and feathers." Blocks cut to a length of 20 to 30 feet are turned over on the side and hoisted up from the quarry by derricks.

Milling of Bedford Limestone. Since Bedford limestone is soft compared to granite, different processes can be utilized in milling. Slabs and blocks are sawed out first by steel gang saws with clean silica sand or crushed cherty rock called "chats" as abrasive. Diamond saws are satisfactory for Bedford limestone. A saw consisting of a straight steel blade with diamond teeth on the cutting edge is used sometimes for single cuts. Circular saws with diamonds set in the circumference of the steel blade, 4 to 6 feet in diameter and about ¼ inch thick, are used for cutting up blocks and slabs. Diamond saws must be cooled with water. Silicon carbide rotary saws are also used, particularly for short and shallow cuts.

Planers are generally used to obtain smooth surfaces and desired dimensions of blocks and slabs. The cutting tool is mounted on an adjustable frame, and the stone is fed repeatedly to the tool by means of a moving bed or "platen." Sides as well as top surfaces may be planed simultaneously. Specially shaped tools are required for cutting moldings. A silicon carbide planer consisting of two vertical saws with a smaller diameter drum mounted between them is sometimes used to trim the sides and smooth the surface in a single cut.

Carving is done by hand or by means of pneumatic tools. Since Bedford stone is readily carved and does not tend to split on bedding planes, it is extensively used for carved figures, emblems, decorations, etc., for churches, chapels, libraries, and other public buildings.

Surface Finishes of Bedford Limestone. In addition to sawed surfaces whose roughness can be controlled by selection of suitable abrasives, and planed surfaces, other types of finish are frequently required to give desired architectural effects. A "tooled" surface consists of fine parallel grooves made by a planer or pneumatic tool having fine teeth. A "four-cut" surface is made with a planer tool having approximately four teeth per inch of width. A "small-fluted" surface consists of small, parallel corrugations. A bush hammer having a face with small projections produces a rough, pitted surface known as a "hammered" surface. A surface having indentations made by means of a sharp-pointed tool is called a "hand-picked" surface. Smooth or "rubbed" surfaces are obtained by hand or machine rubbing with an abrasive such as sand and water.

PROPERTIES OF BUILDING STONES

465. Selection of Building Stone. The selection of a proper stone for construction purposes is dependent to a great extent upon the climate where the stone is to be used. The range of changes of temperature, the average humidity of the atmosphere, the possibility of acid fumes in the atmosphere of many cities, and the possibility of the stone being subjected to high temperatures by fire are among the considerations which must be carefully taken into account. Very often the only considerations given weight by an architect are the cost and the appearance. He is very likely to take great care in securing a color that harmonizes with the general scheme of the structure, while wholly overlooking the question of satisfactory weathering qualities.

The actual mechanical strength of stone is seldom of great importance, for stones in masonry structures can never be loaded to their full capacity on account of the comparative weakness of the mortar joints.

466. Properties of Various Stones. *Durability.* The durability of stones depends upon ability to withstand weathering agencies, and the structure, texture, and mineral composition are the real determining factors. Joint planes, cracks, or other structural imperfections afford an opportunity for water to enter and for disintegration to begin through frost action. Stones of coarse-grained texture are more subject to the disintegrating influence of temperature changes than fine-grained ones, and dense stones, owing to their practical imperviousness, are less likely to be injured through frost action than porous ones. Of the mineral compounds which make up our common rocks, sulfides are among the least resistant to weathering agencies; iron compounds in general are undesirable in large quantities; calcium and magnesium carbonates weather rather rapidly; aluminates weather less rapidly; silicates are most resistant to decay. It must not be overlooked in this connection that the three factors, structure, texture, and mineral composition, are simultaneously operative, so that a very dense, fine-grained stone made up principally of carbonate may weather well, whereas a porous or structurally imperfect stone made up principally of silica may weather poorly.

Absorption. The absorption or absorptive power of stones is represented by the weight of water that can be absorbed, expressed as a percentage of the dry weight of the stone. Absorption is directly dependent upon the porosity of stones, though this relation is not necessarily any fixed ratio. The gain and loss of moisture when a stone is first exposed in a damp or wet situation, and then dried, will be most rapid if the pores are large or straight, and least rapid if they are small or tortuous.

It appears from tests that the absorption of igneous and metamorphic rocks rarely exceeds ½ per cent. The sandstones absorb at least ten times as much as granites, marble, and slate, and the limestones absorb even more moisture than the sandstones.

Expansion and Contraction. Stones, like most other materials, expand upon being heated and contract when cooled. Unlike most other materials, however, they do not quite return to their original volume when cooled after heating, but show a swelling which is permanent. Experiments made at the Watertown Arsenal by heating from 0° to 100° C. (32° to 212° F.) and cooling through the same range showed the permanent increase in length for the various stones tested to be from 0.02 to 0.045 per cent.

The coefficient of temperature expansion per degree F. for various building stones was found in a series of tests at the Watertown Arsenal to be very variable, the range of values found being as follows: granites, 0.00000311 to 0.00000408; limestones 0.00000375 to 0.00000376; marbles 0.00000361 to 0.00000562; sandstones 0.00000501 to 0.00000622.

Frost Resistance. Stones can be disintegrated by frost action only when the pores are practically filled with water before exposure to freezing temperatures. As stones seldom are used under such conditions that the maximum amount of water is absorbed, instances of injury to good building stones by frost action are very rare. Experimental work on the resistance of stones to disintegration by frost indicates that the pores can be filled with water, so that the subsequent expansion upon freezing will cause rupture, only by means of high pressure or by first exhausting the air by a vacuum. It will be apparent, therefore, that only stone of the greatest absorptive power combined with low structural strength can ever be injured by frost action under the conditions encountered in practice.

*Fire Resistance.** Practically all building stones are seriously injured if exposed to such high temperatures as may be encountered in fires, and particularly so if exposed to the combined action of fire and water. The cause of disintegration is usually considered to be the internal stresses caused by unequal expansion of unequally heated portions of the material. This explanation is rendered more forcible by the observed fact that, if highly heated stones are suddenly cooled on the exterior by application of water, the resultant disintegrating action is much more pronounced than when the cooling is slow. Probably the texture of the stone and the relative coefficients of expansion of its individual mineral constituents are also factors of importance.

Experience has shown that granites are particularly poor fire resistants. Probably on account of the irregularity of the structure and the complexity of the mineral composition, granites crack irregularly and spall badly. The coarse-grained granites are most susceptible to the action of fire and water, and the gneisses often suffer even more severely because of their banded structure.

Limestones suffer little from heat until a temperature somewhat above 600° C. (1112° F.) is reached, at which point the decomposition of the stone begins, owing to the driving off of carbon dioxide. The stone then has a tendency to crumble, because of the flaking of the quicklime formed.

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* Ries and Watson: "Engineering Geology," p. 446.

Curiously enough, the limestones do not suffer so much by sudden cooling as by slow cooling.

Marbles, owing to the coarseness of the texture and the purity of the material, suffer more than limestones at temperatures below the point where calcination begins. The cracking is irregular, and the surface spalls off as in granites.

Sandstones, especially if of a dense, non-porous structure, suffer from high temperatures and sudden cooling less than most other building stones. The cracking of sandstones that does occur appears mostly in the planes of the laminations, which should be horizontal planes as the stone is set. These cracks are therefore not so serious as irregular cracks. Sandstones in which the cementing ingredient is silica or lime carbonate are better fire resistants than those in which the grains are bound by iron oxide or clay.

Mechanical Properties of Stones. The tabulation of mechanical properties of the principal classes of building stone given in Table XLII has been compiled from various sources to serve as an approximate guide in the selection of a building stone.

TABLE XLII

MECHANICAL PROPERTIES OF BUILDING STONES

Kind of Stone	Comp. Strength, lb. per sq. in.	Modulus of Rupture, lb. per sq. in.	Shearing Strength, lb. per sq. in.	Weight, lb. per cu. ft.	Modulus of Elasticity, lb. per sq. in.
Granite	15,000	1,200	1,800	156	6,000,000
	30,000	2,200	2,700	165	10,000,000
Limestone	4,000	250	1,000	145	4,000,000
	20,000	2,700	2,000	170	14,000,000
Marble	10,000	850	1,000	168	4,000,000
	16,000	2,300	1,700	178	13,500,000
Sandstone	7,000	500	1,200	133	1,000,000
	20,000	2,000	2,500	150	7,500,000
Slate	......	7,000	.....	170	12,000,000
	......	11,000	.....	180	....

If conditions exist which necessitate an accurate knowledge of the physical properties of the stone to be used, safety lies only in actual tests from stone taken from the exact source from which it is expected to draw the supply. In any instance very large safety factors (often from 15 to 35) are allowed in design.

Two properties of slate not listed above are of considerable importance, namely, toughness and color permanence. Good slates will show an ultimate deflection of about ¼ inch when centrally loaded on a 22-inch span. Color permanence cannot be readily determined in the laboratory. The record of the slate under actual service conditions is the best criterion for this important property.

It will be noted, by reference to the preceding table, that any given stone shows wide variation in properties. These variations are to be expected from the wide range of the component minerals and consequent variations in chemical composition, and in igneous rocks the rate of cooling also plays an important part. The properties of limestones are affected by their manner of formation. Marbles show variations due to the completeness of crystallization and size of the component crystals. Sandstones are affected by the character of the cementing material which holds the quartz particles together as well as by the size of the particles. Practically all stones are also affected by the type and degree of metamorphism which is present.

STONE MASONRY

467. Stone Masonry. The actual *compressive strength* of stone masonry has not been satisfactorily determined experimentally. The tests which have been made do not form a sufficient basis for the determination of the relative strengths of the different classes of masonry, or the relative strengths of masonry of the same class constructed of different kinds of stone.

The manner of failure of masonry under compression is almost invariably by the compressive failure, followed by lateral flow, of the mortar, thus setting up tensile stresses in the stone which open transverse cracks.

It is obvious that the integrity of a masonry structure is destroyed by this failure of the mortar in the joints. In fact, it is only with the strongest mortars laid in the thinnest possible joints that the real strength of building stone can be developed. With the common mortars, as generally used, the data at hand would tend to indicate a strength for stone masonry not above two-fifths of the compressive strength of the stone itself. With thick joints and lime mortars, this may fall as low as one-tenth the strength of the stone.

Allowable Loads on Stone Masonry. Conservative building laws recommend approximately the values given in Table XLIII as safe pressures for the different classes of stone masonry:

TABLE XLIII

ALLOWABLE LOADS ON STONE MASONRY

KIND OF MASONRY	ALLOWABLE PRESSURE, lb. per sq. in.
Rubble, uncoursed, in lime mortar	60
Rubble, uncoursed, in Portland cement mortar	100
Rubble, coursed, in lime mortar	120
Rubble, coursed, in Portland cement mortar	200
Ashlar, limestone, in Portland cement mortar	400
Ashlar, granite, in Portland cement mortar	600

STONE AS ROAD METAL

468. General. In highway construction stone may appear as cut blocks or cobblestone in paved streets; as crushed stone in broken-stone roads, bituminous macadam pavements, and bituminous or cement concrete pavements; as sand or gravel in earth and gravel roads. The desirable qualities and characteristics are somewhat variable, depending upon the type of road, the severity of traffic, and the kind of vehicle commonly passing over it.

469. Properties. The actual crushing strength, like that of building stone, is, on the whole, of but secondary importance. The special qualities most commonly noted for road building stone are toughness, resistance to wear or abrasion, and hardness. Occasionally the absorption, specific gravity, and a highly specialized property known as cementing value may become factors worthy of consideration, but generally they are of very minor importance.

These qualities are determined by special methods of testing which have been carefully standardized by the United States Bureau of Public Roads and the American Society for Testing Materials. The standards for comparision are wholly arbitrary and always require special apparatus for their determination.

Toughness is determined from a 1-inch cylindrical specimen 1 inch long. This specimen is fractured by the impact of a 2-kilogram hammer transmitted through a standardized plunger. The vertical drop of the hammer (1 centimeter for the first impact) is increased 1 centimeter for each blow. The number of blows required to produce fracture is the measure of the toughness.

Resistance to wear, or the "French coefficient of wear," is determined by rattling 50 pieces, roughly cubical and of approximately uniform size, weighing in the aggregate approximately 5 kilograms, in a Deval abrasion machine which consists of a closed cylinder that rotates about an inclined axis. The loss in weight through a No. 12 U. S. standard sieve after 10,000 revolutions may be expressed as "per cent of wear," or in terms of the "French coefficient," which is 2000 divided by the total loss in grams, or 40 divided by the per cent of wear.

This test is modified for gravel by using a charge of 5 kilograms of gravel, graded to conform to a specified grading. To this charge are added six cast-iron spheres, each weighing approximately 0.95 pound. The manner and duration of the test are the same as above. The results of this test are always expressed in terms of per cent of wear.

Los Angeles Abrasion Loss. The Deval abrasion machine has been superseded in many laboratories by the Los Angeles abrasion machine, which consists of a cylindrical drum 28 inches in diameter and 20 inches in length, mounted longitudinally on a horizontal shaft and having a shelf 4 inches wide extending from end to end on the inside. The drum is revolved 500 revolutions at a rate of 30 to 33 revolutions per minute. The drum is charged with 12 steel or cast-iron balls weighing 5000 grams for stone of coarse grading or with 11 balls weighing 4583 grams for stone of fine grading. The sample consists of 5000 grams of gravel or commercially crushed stone which is graded to conform to a specified coarse or fine grading.

The test charge is caused to drop from the shelf instead of to slide or roll as in the Deval test. The percentage of wear is determined from that portion which, after test, will pass a No. 12 U. S. standard sieve. Tests can be made more rapidly and more accurately by means of the Los Angeles test than by the Deval test, and better agreement has been obtained between wear and the service record of materials in road surfaces.

Hardness is determined by pressing a 1-inch cylinder endwise against a revolving disk upon which is fed clean crushed quartz of standard size. A pressure of 1250 grams is maintained, and 1000 revolutions constitute a test. The hardness is expressed by the relation $H = 20 - \frac{1}{3} W$, where W is the loss of weight in grams.

Soundness is sometimes determined by means of a saturated solution of sodium sulfate. Pieces of stone like those for the wear test are immersed in the sulfate solution for 20 hours and dried for 4 hours, the procedure being repeated until 5 cycles have been completed. Stone which shows no spalling or disintegration under this treatment is held to be "sound" and may be expected to resist disintegration under the action of frost and other common weathering agencies.

470. Significance of Tests. Materials having a Los Angeles abrasion loss of 40 per cent or less may be expected to give satisfactory results in road surfaces.

It is probable that the Los Angeles abrasion test will in time supplant the Deval abrasion test. The Los Angeles percentage of wear may also be a sufficient index of toughness and hardness so that the tests for toughness and hardness may become unnecessary.

At present, however, the following classifications may serve as a guide in the choice of available stone for road material:

Property	Low	Medium	High
Toughness	Below 13	13 to 19	20 and over
French coefficient	Below 8	8 to 13	14 to 20
Hardness	Below 14	14 to 17	17 and over

Various state and municipal specifications indicate the following requirements for general high-grade road construction:

STONE

Toughness	(min.)	6 to 10
Per cent of wear	(max.)	4 to 8
French coefficient	(min.)	5 to 10

Where traprock is specified the requirements are usually more severe, the percentage of wear often being held as low as 3 with the toughness value advanced to 15–18.

GRAVEL

Deval per cent of wear (max.) 10 to 15

471. Qualities of Rock Types. *Trap* is hard, highly abrasive, resistant, and tough, if free from fine joints and seams. (It should be noted that with the true traprocks are commonly associated, at least commercially, many other more or less fine-grained, dark-colored, igneous rocks. These are generally inferior to true trap, particularly in regard to toughness.) True traprocks may be used for all classes of modern road construction.

Granites and similar coarse-grained rocks are usually lacking in toughness, possess moderate wear resistance, and evince great variation in hardness. In general they should not be used for road surfaces, except in the form of paving blocks or in base courses.

Limestone is a stone that is widely used in road construction. Many localities furnish varieties with good wear resistance and fair toughness, though not very hard. Limestone dust has a good cementing value. Some limestones are too soft for road material. Limestone is largely used as aggregates for water-bound and bituminous macadam and for bituminous and cement concrete.

Sandstones of the better qualities and *quartzite* are very tough, show satisfactory coefficient of wear, and are quite reasonably hard. (It should be noted that sandstone may be formed with a number of cementing materials of which iron oxide is the most desirable, while lime and clay will produce weak and soft varieties.)

Shales, slates, and *schists* in general are very unsatisfactory as road material. This is due in part to their foliation, which causes the rock to break into flakes.

Fieldstone must of necessity be of very heterogeneous character and hence of variable characteristics. Availability and other exigencies often lead to its use, frequently resulting in very uneven wear of the road.

QUESTIONS

1. State the usual geological classification of rocks. Define each classification, and give a common example of a rock in each classification.

2. Name five commonly used building stones, state their geological classification, and give their relative values as to strength, durability, ease of cutting and dressing, appearance, and fire-resisting properties.

3. Describe the quarrying and milling of granite and Bedford limestone.

4. State what you would do in passing upon the quality of a building stone for use in an important structure, assuming that you could visit the quarry and observe similar stone in a structure of some age, and that you have facilities for making laboratory tests.

5. Name and describe the common tests for stone as road metal. State the significance of each of these tests.

6. Describe the qualities of three rock types used as road metal.

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SECTION 5

BRICK AND CLAY PRODUCTS—REFRACTORY AND HEAT-INSULATING MATERIALS

CHAPTER XVIII

BRICK AND CLAY PRODUCTS

472. General Classification. The principal clay products used structurally are building brick, paving brick, firebrick, terra cottas, and various forms of tile.

Brick * may be made from a large number of different classes of material, the main essentials being that the material be of a mineral nature and possess a considerable degree of plasticity when dampened.

Building brick are usually made of a mixture of clay and sand, to which coal and other foreign substances are sometimes added, which is mixed and molded in various ways, after which it is dried and burned.

Paving brick are made primarily as a material for street pavements, though certain types are suitable for building purposes.

✓ Firebrick are of such a nature that they will withstand high temperatures. Their structural uses are largely confined to linings of flues, stacks, etc. They are discussed in Chapter XIX.

Terra cotta is made of selected clays in much the same way as ordinary brick. Architectural terra cotta is used for decorative effect on buildings, and terra cotta lumber and hollow blocks for both interior and exterior walls of buildings and as fireproofing to protect steelwork.

✓ Tiles, made by burning various classes of clay, are used in various forms as roofing tile, wall or floor tile, drain tile, and sewer pipe.

473. Brick Clays. Clays for brick making must develop proper plasticity and be capable of drying rapidly without excessive shrinkage, warping, or cracking and of being burned to the desired texture and strength. If a clay contains too high a percentage of such impurities as iron oxide,

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* The term "brick," as defined by the American Society for Testing Materials, is understood to mean a unit of burned clay or shale. When other substances are used such as lime and sand, cement and sand, fireclay, or adobe, the term "brick" should be suitably qualified.

lime, magnesia, and alkalies, either the clay must be rejected or the impurities removed or neutralized.

Residual, sedimentary, and glacial clays are all used for brick making when they possess a sufficient plasticity for molding and burn to a body of the proper hardness and color, but sedimentary clays are usually most satisfactory. The following classification of sedimentary clays is made by Ries:

- *Marine clays or shales.*
  - White-burning clays. Ball clays and plastic kaolins.
  - Fireclays or shales, buff burning.
  - Impure clays or shales.
    - Calcareous.
    - Non-calcareous.
- *Lacustrine clays* (deposited in lakes or swamps).
  - Fireclays or shales.
  - Impure clays or shales, red-burning.
  - Calcareous clays, usually of surface character.
- *Floodplain clays* (usually impure and sandy).
- *Estuarine clays* (deposited in estuaries, mostly impure and finely laminated).

Marine deposits of clay often stretch for hundreds of miles to a depth of 30 feet or more. Their composition is remarkably uniform and, except for those which are too high-limed or are excessively plastic, include the best clays obtainable for brick manufacture.

Lacustrine and estuarine clays occur in beds of limited extent and ordinarily of no great depth. They may be sandy and are less valuable for brick making than the marine clays.

Floodplain clays are sometimes very sandy and often contain pockets of sand. They are sometimes very calcareous and cannot be advantageously used.

The most common materials in the manufacture of structural clay products are fireclay, shale, and clay. Fireclay is largely used in manufacturing refractory materials such as firebrick. It has a fusing point as high as 1760° C. (3200° F.), and its fluxing impurities such as iron oxide, lime, magnesia, and alkalies are small. Most shales are not soluble in water except when ground up, those suitable for the production of clay products then becoming plastic with addition of moisture. Common clays vary widely, both in chemical composition and in physical characteristics which affect both color and physical properties of the finished product. Low-grade clays and shales are extensively used in the making of common brick of medium grade, generally red in color. These clays are easily obtained from deposits, mold easily, and burn hard at comparatively low temperatures with small loss from warping and cracking.

A very plastic clay is likely to shrink, crack, and warp in drying and be very hard after burning. The presence of coarse sand in suitable amounts tends to prevent shrinking and cracking in burning, but an excess of silica in the shape of sand destroys cohesiveness. Iron oxide acts as a flux and adds greatly to the hardness and strength of brick. It causes the clay to burn buff or red in color according to the amount of iron oxide present. Lime considerably in excess of iron causes the brick to burn buff and shrink strongly as vitrification is approaching. The lime must be in a very finely divided state so that it will be completely hydrated or fluxed in the process of manufacture of the brick. The presence of lumps of unhydrated lime which become hydrated after long periods is the cause of unsightly defects on brick walls called "lime-pops." Magnesia and alkalies also act as fluxes.*

STRUCTURAL CLAY PRODUCTS

474. Characteristics of Principal Processes. The three most common methods of manufacture of structural clay products are the stiff-mud, the soft-mud, and the dry-press processes. The fundamental principles of preparing the clay are the same in all three processes, which differ only in details and in degree of refinement. In the stiff-mud process the clay contains just sufficient moisture and plasticity to be extruded through a die; in the soft-mud process it is too wet to be forced through a die without drying and hence must be molded; in the dry-press process it is in a nearly dry state and is molded into shape under high pressure. This last method makes possible the use of non-plastic materials.

The flow of clay from the pit to the finished product through typical operations in a modern plant is illustrated in Fig. 123. Processes of manufacture of structural clay products may be divided into the following steps:

Selection and "winning" of suitable clay.

Storage.

Preparation of clay, including cleaning, removing large pebbles, grinding, and screening.

Mixing and tempering to produce plasticity, uniformity, and homogeneity.

Shaping into units by extruding machines and cutters, molds, presses, or other appliances.

Drying, either by natural or artificial means.

Burning, usually in kilns.

Winning. "Winning" is the term applied to obtaining the clay from the pit. Clays are mostly obtained by surface digging or quarrying, and to some extent by mining, depending upon the nature and location of the

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* See Table LI in Art. 519 for composition of brick clays.

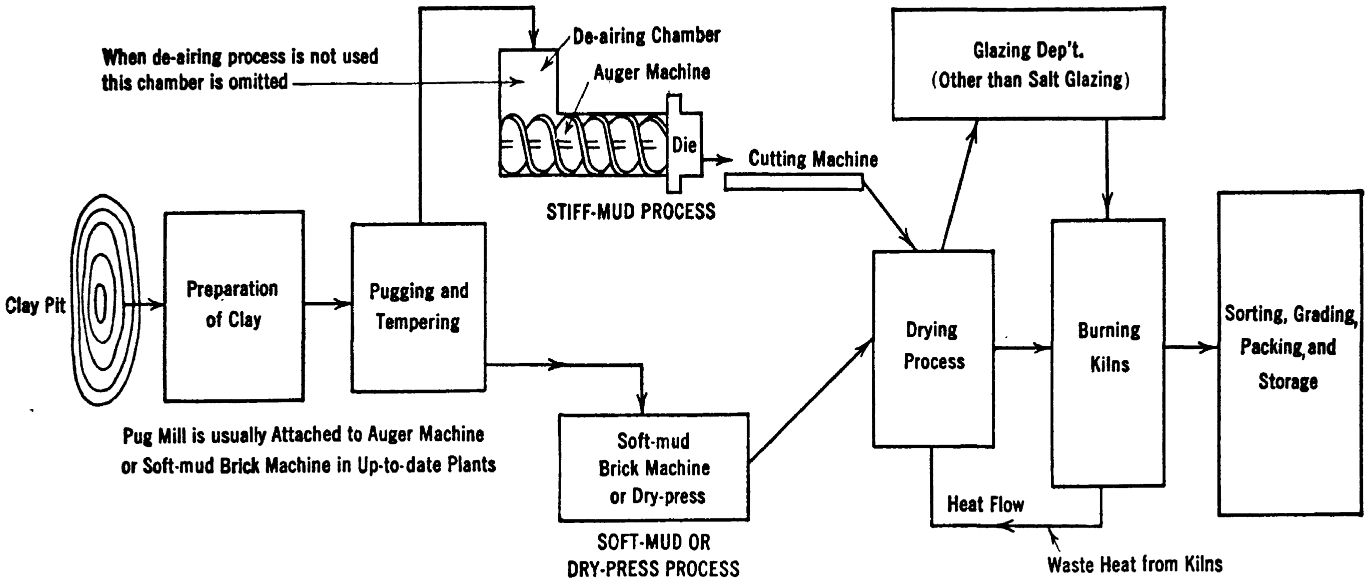

FIG. 123.—Flow Chart Showing Typical Operations in a Modern Plant for Manufacturing Structural Clay Products.*

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* F. E. Emery: The Manufacture of Structural Clay Products, *Civil Engineering*, v. 7, No. 11, November, 1937, pp. 755-759.

deposit. In shallow banks a machine called the shale planer is sometimes used; power shovels are frequently used in excavating clay from surface pits. Many shales are so solidified that they have to be loosened by blasting. The quarrying method is suitable for some pits, the deposits being worked in benches.

Storage. After the clay has been obtained from the pit, it is usually stored in large piles or bins until required in the plant. Exposure to the air improves the workability of many clays. In many soft-mud-process plants, the clay is transported directly to the preparation plant, or even directly to the pug mill.

Preparation of Clay. The preparation of clays is much the same in all three processes. Some clays require considerable preparation, others very little. The operations described here are typical. Clay transported from the pit or storage bins in cars or on belt conveyors is usually delivered to a granulator which consists essentially of a semicylindrical tank within which revolves a steel shaft equipped with knives so pitched that they not only break up chunks of clay and mix and granulate the material, but also function as a screw conveyor, discharging the clay at the end of the machine. If the clay contains large stones, they may be eliminated by putting the clay through conical rolls which tend to crush small chunks of clay and discard the stones. The clay is then ground if necessary by grinding wheels called "mullers," weighing about 5 tons each.

Pugging. After the preliminary steps of preparation, the clay is tempered, the object of which is to produce a homogeneous plastic mass. This is usually accomplished in a pug mill, which is a horizontal cylinder provided with one or two power-driven shafts with blades rigidly attached. The revolving blades slice up and thoroughly mix the mass until it is ejected through an opening at one end. During the pugging operation, it may be necessary to add sand to reduce shrinkage, or more water to produce the desired plasticity.

475. Stiff-mud Process. In the stiff-mud process the clay is only sufficiently moist to possess the requisite coherence under moderate pressure, which results in economy of time in drying and of fuel in burning. The clay may be pugged either in a separate pug mill or in a pug mill attached to the brick machine itself. The clay is delivered to the brick-making machine which forces the plastic mass out through a molding die in a stream called a "column." The die molds the mass into the desired shapes for brick, hollow tile, or other forms, and as the column is extruded it passes over a wire cutting table where it is cut into the desired lengths.

The brick machine may be either of the *auger* or the *plunger type.* The auger machine consists of a closed tube of cylindrical or conical shape in which, on the line of the axis of the tube, revolve a shaft to which are attached the auger and auger knives. The knives are so arranged as to cut and pug the clay and force it forward into the auger. The function of the auger is to compress and shape the clay and force it through the die. The column of clay as it issues from the die travels along the table on an endless belt which is supported on rollers. At intervals the operator throws a lever which swings downward a rigid frame, across which a series of wires are tautly stretched. By this means the column is cut into sections of desired length.

If the cross-section of the column is the same as the end of the brick, the bricks are called "end-cut" and if the cross-section corresponds to the side of a brick, they are "side-cut." When end-cut bricks are made the clay often issues from the machine in several separate streams. Structural clay tile, drain tile, and similar shapes are all end-cut. In the size of the die and in cutting to length allowance is made for the shrinkage that results from drying and burning. All dies must be lubricated by oil, water, or steam, as few clay columns will run through freely without having their corners pulled back or being otherwise damaged. Lubrication also reduces power consumption.

After the units are cut to length they pass to a belt conveyor where they are inspected. The satisfactory units are taken off by hand and sent to the dryer, the imperfect ones being returned to the pug mill for retempering and remolding.

The great majority of bricks in the stiff-mud process are made in the auger type of machine. The plunger type of machine is used to some extent, however. In the plunger type, the clay after pugging is forced into a closed chamber which acts as a feeder for the pressure cylinder into which it discharges, the amount discharged being subject to control. The forward motion of the plunger now compresses the clay and forces it through the die. The clay column thus formed passes on to the cutting table and is cut by wires in the manner described above.

De-airing is a recent and important development in the stiff-mud process. It is accomplished in a de-airing chamber attached to the auger machine through which the clay passes. The clay is broken up and shredded as it enters this chamber, where a vacuum of 15 to 29 inches is maintained. Some of the advantages of de-airing are greater strength in the green and in the fired body, increased workability and plasticity, and better utilization of the inferior clays. However, some clays do not respond well to the de-airing process.

476. Soft-mud Process. In the soft-mud process all structural clay products are molded by machinery, except for special products. This process is used where the clay is too wet to be forced through a die without drying and hence must be molded. In large modern plants, brick are molded under pressure in a soft-mud brick machine which tempers the clay in its pugging chamber, sands or wets the molds, presses the clay into 4 to 9 molds at a time, strikes off the excess clay, bumps the mold uniformly, and dumps the brick onto a pallet with each revolution. The pallets of brick are carried away to the dryer as fast as made. The operation of the machine is automatic, the only hand labor being that required to feed pallets and sand into the machine.

There are two classes of soft-mud brick: *sand-struck* and *water-struck*. In the sand-struck method the inside of each mold is coated with a thin layer of sand to prevent the clay from sticking. In the water-struck method, also called "slop-molding," the molds are dipped in or sprayed with water to prevent sticking. Sand-molding is the more common method, the bricks being usually cleaner and sharper than water-struck brick, although some very good grades of brick are water-struck.

477. Dry-press Process. The dry-press process permits the use of non-plastic and relatively dry clays in the manufacture of high-grade products. The best results are obtained when the clay contains from 7 to 10 per cent moisture. The clay is usually prepared by disintegrator, granulator, grinder, and pug mill, and then is fed into molds in the dry-press machine by a reciprocating charger located below the hopper. At each revolution of the machine the charger moves forward, and when it is directly over the molds the bottom plunger in the molds descends, allowing the molds to be filled with clay. The charger is withdrawn, the clay supply shut off, and the top and bottom plungers move toward each other in the molds, compressing the clay between them. The pressure is now relieved and then applied a second time, the compression of the clay being greater than at first and ranging from 550 to 1500 pounds per square inch. The upper plunger is now withdrawn, and the bottom plunger raises the brick to the level of the top of the mold. The next stroke of the plunger pushes the finished brick upon the mold table, whence it is removed to the dryers.

Dry-pressed bricks are very compact, show high compressive strength, and are well formed, but they are not generally considered to be as durable as bricks produced by the stiff-mud or soft-mud processes. They are, however, extensively used as face brick. The term "pressed brick" is proper only in referring to brick made by the dry-press process.

478. Drying. As wet clay units come from the different brick machines, they contain from 7 to 30 per cent moisture, depending on whether the dry-press, stiff-mud, or soft-mud process has been used. Moisture in clay ware may be classified as equilibrium moisture and free moisture. Equilibrium moisture is that moisture in the material which exerts a vapor pressure equal to that exerted by the surrounding air of given temperature and humidity. Free moisture is the moisture other than equilibrium moisture, and is held largely in the pore spaces. Most of the free water is removed in the drying process, and the remaining moisture during the burning process.

Structural clay products may be dried either by natural or artificial means. Natural drying may be accomplished by placing the molded units in the open air on racks which allow a maximum access of air and sunlight on all sides. In order to prevent injury by rain, the racks are covered with a light roofing or are placed in sheds. These sheds are permanent structures provided with a weathertight roof and with side walls either fitted with shutters or built of perforated bricks. Soft-mud brick often require from 3 to 6 weeks' drying; stiff-mud brick are sometimes burned after less than 1 week on the drying racks.

Mechanical dryers, which permit of automatic control of temperature, humidity, and air velocity, have come into general use. As the free water of the clay body is removed, the clay particles tend to coalesce, causing shrinkage. The general effect of such shrinkage is to increase the resistance to moisture flow in the dried layers. If the drying is carried on too rapidly as by means of hot dry air, the moisture is removed from the surface of the solid more rapidly than the interior of the solid can deliver moisture to the surface, so that the surface hardens and cracking occurs. It is desirable to dry clay ware with moist air, reducing the drying rate to the point where diffusion of water to the surface can keep up with the vaporization at the surface. This dries the clay rather uniformly throughout and minimizes the effects of local shrinkage by keeping the shrinkage uniform. These conditions may be obtained in the humidity system of drying, in which highly humidified warm air is admitted to the room and the ware is heated up until the vapor pressures of air and clay are about equal. The relative humidity of the air surrounding the clay then is decreased by raising the air temperature. This sets up a difference in vapor pressure which draws moisture gradually from the ware, and the action is continued until most of the free moisture has been removed.

The continuous tunnel dryer is very common for drying of bricks. The bricks are piled on cars which move slowly through the tunnel, which is heated either by hot air or by steam pipes. The tunnels are usually built of masonry and may be 100 feet or more in length.

The average time necessary for drying structural clay products is about 3 days, and the temperature required is from 38° C. (100° F.) to 149° C. (300° F.). The heat may be supplied directly or it may be waste heat recovered from the kilns.

479. Burning. The burning of structural clay products in a kiln requires an average time of 3 to 4 days, after which the openings are tightly closed and the kiln allowed to cool very slowly.

The process of burning may be conveniently divided into the following four stages:

Water Smoking. During this period which requires about 12 hours the free water in the clay is driven off under temperatures ranging from 125° C. (257° F.) to 175° C. (347° F.).

Dehydration. Dehydration consists of expelling chemically combined water by breaking down the clay molecules. It begins at about 425° C. (797° F.) and is completed at about 750° C. (1382° F.).

Oxidation. Oxidation begins during the dehydration stage. All combustible matter is consumed, carbon is eliminated, the fluxing materials are changed to oxides, and sulfur is removed.

Vitrification. Vitrification is the contracting and filling-up of the pore spaces of the clay. Common building bricks are not vitrified according to the definition of the term but are burned only to the incipient stage at a temperature seldom above 1200° C. (2192° F.) when the clay has been softened to a point where the larger grains stick together but not all the pores of the mass are closed. Paving bricks are completely vitrified, the mass being rendered impervious. Paving bricks require a high temperature for vitrification since they contain small amounts of fluxing materials. Firebricks require a very high temperature.

480. Kilns. Brick kilns may be divided into two general classes, *intermittent* and *continuous kilns.* Intermittent kilns may be further subdivided into up-draft and down-draft kilns. Continuous kilns are seldom used in connection with hand molding or in small plants of any type.

Up-draft Kilns. The old-fashioned up-draft kiln consists of the green bricks themselves piled in such a way as to form a series of arched openings extending entirely across the kiln. The outside is encased with brick, usually soft-burned from a previous burn, and then plastered with mud to keep in the heat. The top is covered with earth or sometimes is roughly roofed. The fires are built in the arches. The bricks nearest the fires are badly overburned, sometimes to vitrification, and are called *arch brick.* The bricks at the top of the kiln are underburned, and are called *salmon brick.* Only the intermediate bricks are first-class building brick.

The modern up-draft kiln has permanent sides made of brick masonry 12 to 16 inches thick, and the heat is generated in ovens outside. The flames and hot gases enter the kiln through fire passages in the walls. This type of kiln is more economical of fuel than the early type, and yields a much larger percentage of first-class brick.

Down-draft Kilns. Kilns of this type require permanent walls and a tight roof. The floor has openings connecting with flues leading to a stack. Most down-draft kilns are built in a circular or beehive shape, but some are rectangular.

Heat is generated in outside ovens, and the flames and gases enter the kiln through vertical flues carried to about half the height of the kiln. The heat therefore enters the brickwork at the top and is drawn downward by the chimney draft to the flues below the floor, and thence to the chimney or stack.

The down-draft kiln has a much higher efficiency than the up-draft kiln, and it is commonly used in burning structural clay tile of all types, terra cotta, pottery, and brick which require close control of heat and uniform burning.

Continuous Kilns. There are many types of continuous kilns, but all depend on practically the same principle. A number of chambers are connected in series, and also individually connected with a stack. The stack flues and the flues between chambers are provided with dampers. While one chamber is burning, the waste products of combustion are forced to traverse the whole series of charged chambers before reaching one that is open to the stack. The material is thus preheated before being fired. The down-draft principle is utilized, the flue openings being in the floor. This type of kiln is expensive to install, but the percentage of first-class brick is also high, provided that the fuel is burned on grates or in troughs, instead of in contact with the brick.

The tunnel type of continuous kiln is built both as a straight and as a circular tunnel through which the clay products pass while being burned. The bricks are loaded on special cars which are transported through the tunnel at the proper speed through the water-smoking, dehydration, oxidation, vitrifying, and cooling zones. The heat conditions in each zone are carefully controlled. The advantages of the tunnel kiln are greater heating efficiency and more uniformly burned products.

481. Classification and Uses of Product. In emptying the kiln, the bricks are separated into various grades or qualities according to the degree of burning and freedom from imperfections. All bricks that show cracks or excessive kiln-marking, as well as those which are badly warped, must be put into an inferior class. Common brick are usually divided into three grades:

Arch or *hard brick,** those which, owing to their position in the kiln, have been overburned, are apt to be misshapen, and are used only in footings and for the "filling" of brick masonry.

Red or *well-burned brick,* which amount to about half the output of the up-draft kiln and constitute the best grade of brick for all general construction purposes.

Salmon or *soft brick,* those which have not been sufficiently burned, are too weak for first-class construction but are adequate for masonry

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* Certain types of architecture require the use of warped, seamed, and imperfect bricks.

filling and unimportant work not calling for high strength or great durability.

The standard size of building brick is 2¼ by 3¾ by 8 inches.

Pressed brick or *face brick* are made by the dry-clay process as above noted or, using the commonly accepted meaning of the term, by repressing soft- or stiff-mud process brick. They are smooth and hard, have true surfaces and sharp angles, and can therefore be laid with a minimum thickness of mortar joint. The advantages they possess in appearance favor their use in the facing of masonry.

Glazed and Enameled Brick. Glazed brick are those made by coating one side of unburned common brick with a thin layer of what is called "slip," a composition of ball clay, kaolin, flint, and feldspar, and then applying a second coat of transparent glaze resembling glass. The slip gives the color to the brick, and the glaze melts upon firing the brick, and forms a smooth transparent coating over the white slip.

Enameled brick are made from a clay of peculiar character, generally containing fireclay, and the enamel is applied either to the unburned or to the finished brick. In burning, the enamel fuses and unites with the body of the brick. Enameled brick are expensive and more difficult to make than glazed brick, but are generally considered the more durable.

Both glazed and enameled brick are particularly adapted for interior finishing, lavatories, hospitals, etc.

High-grade bricks, when struck together, give out a clear metallic ring that is very different from the dull sound produced by inferior bricks.

SAND-LIME BRICK

482. General. Sand-lime brick are not made from clays, but, since their uses are identical with those of ordinary building brick, their manufacture will be discussed at this point.

Several classes of brick are manufactured by combining sand and lime in various proportions. Only one of these is important as a commercial article, however, and entitled to the name "sand-lime brick." These bricks are molded under pressure and hardened in an atmosphere of steam.

Bricks are sometimes made somewhat similar to sand-lime brick, but using cement, sand, and a comparatively small amount of hydrated lime. Such bricks are not recognized as a standard, and, although their strength may compare favorably with the best sand-lime brick, their durability is yet to be proved.

483. Materials. Almost any clean sand is suitable if the process is varied to suit its properties. A well-graded sand will make a brick of the lowest absorption and, therefore, the one least likely to disintegrate.

Experiments have shown that the binding action of lime and sand proceeds much more rapidly when the sand is very fine. From the standpoint of density and strength, however, a sand of such composition as to secure a minimum of voids is preferable. A composition of at least 4 parts of sand which is between the 20-mesh and the 100-mesh screen size, to 1 part of sand finer than the 150-mesh, has been found to give a brick of maximum compressive strength.

The Lime. Either high-calcium lime or dolomitic lime may be used, but the former is preferable. The amount of lime required varies from about 5 to 10 per cent.

Preparation of the Sand. The preliminary treatment of the sand is dependent first upon its source, and second upon the details of manufacture. A soft sandstone rock must first be crushed and then screened to separate out the larger particles. Sand obtained by dredging must be dried. If an excess of clay is present, or if it is a seashore sand contaminated with the salts of sea water, washing and subsequent drying are required. If the sand does not contain a sufficient proportion of very fine quartz, it is necessary to pulverize a portion of it in a tube mill or other type of fine-grinding machine and add the pulverized material to the natural sand.

Preparation of the Lime. The preparation of the lime is simply a matter of hydrating or slaking it, before mixing with the sand, unless the sand is very wet. In this event the unslaked lime may be mixed with a portion of the wet sand and thus slaked, and the balance of the sand after being dried is added to the mix. With a moist sand the lime may be slaked to a putty before being mixed with the sand. It is best, however, to have dry sand and dry hydrated lime.

484. Manufacture. *Mixing.* The thoroughness of mixing is the most essential detail of the entire process. Probably the best method of thoroughly incorporating the 5 to 10 per cent of lime used with the sand and water consists in mixing the lime and sand in a tube mill and then adding water to the mix in a pug mill. The latter delivers the mix to a bin where it is allowed to stand for some hours before being delivered to the press.

Pressing the Brick. Owing to the grittiness of the mix it is not possible to make wire-cut sand-lime brick. They are therefore made in a mold in the same manner that dry-press clay brick are made, under pressures as much as 15,000 pounds per square inch.

Hardening. The bricks are not allowed to harden in air, but are hardened in closed chambers subjected to steam under a pressure of 100 to 150 pounds per square inch. The hardening chamber is a horizontal cylinder of steel, provided with a removable steamtight head and tracks upon which cars carrying the bricks are run into the cylinder. The time required for hardening depends upon the steam pressure, being usually between 4 and 10 hours.

MANUFACTURE OF PAVING BRICK

485. General. A good paving brick should be hard enough to resist the abrasive action caused by street traffic; so tough that it will not be broken by the impact of wheels, horses' hoofs, etc.; and non-absorptive, so that it will resist weathering. Its manufacture differs somewhat from that of common brick because the selection of a suitable clay is more limited and burning must be carried out at a much higher temperature, vitrification or at least incipient vitrification being required.

486. The Clay. Surface clays are generally unsuitable for paving brick because, on account of their highly siliceous character, the range of temperatures between incipient and viscous vitrification is so short that only a small portion of the kiln charge is properly burned.

Impure fireclays are used to a slight extent, but are very hard to burn properly. A pure fireclay cannot be vitrified; it is necessary, therefore, that there be present at least from 5 to 7 per cent of fluxing impurities (iron, lime, magnesia, and alkalies). These clays possess one advantage in that it is usually impossible to overburn them, and the burning need not be watched so carefully as that of the surface clays and the shales.

Shales or rock clays are used for practically all paving brick made at the present time. They occur in larger bodies than either of the other classes of clays, and, although the expense of crushing is increased owing to their rock nature, they are so impure that the range of vitrification is often as much as 400° C. (752° F.), making them an especially valuable material for paving-brick manufacture.

Upon delivery at the plant, shales are crushed either in dry pans, rolls, or centrifugal disintegrators. The crushed clay is screened to remove all particles not passed by about a 20-mesh sieve, and delivered to the pug mill where just sufficient water is added to make a stiff mud.

487. Molding and Drying. Practically all paving brick are made by the stiff-mud process, the machine being usually of the auger type. The size of the die is larger than for building brick, since the usual size of paving brick is 4 inches wide by 8½ inches long and 2½, 3, or 3½ inches deep. Usually side-cut brick are made.

The de-airing process is extensively used in order to obtain greater density and strength in the finished paving brick.

Paving bricks are usually laid in pavements with the wire-cut surfaces horizontal so that a rough-textured surface will be uppermost to reduce slipperiness. Paving brick laid in this manner are referred to as "vertical fiber" brick on account of the vertical position of the structure formed in the brick in forcing the clay through a die. Lugs on the ends and on one side of the brick are formed by a special compressing operation for the purpose of providing a proper spacing between the bricks in a pavement so that adequate penetration of a bituminous filler material into the joints may be obtained.

The practice of re-pressing paving brick after forming by wire cutting has been practically discontinued since no improvement in physical properties is obtained.

Paving brick are dried by the same methods as ordinary stiff-mud brick.

488. Burning, Annealing, and Sorting. Paving brick are burned in either the down-draft or the continuous kiln. The burning requires from 7 to 10 days, and the temperature is a bright cherry heat, whereas only a red heat is attained in burning hard building brick. The temperature required varies according to the clay, and the proper temperature of vitrification for a given clay must not be exceeded, since it results in softening of the brick. When the brick are thoroughly burned, the kiln must be tightly closed and allowed to cool down slowly for several days. Thus the brick are annealed and acquire a great deal more toughness than when quickly cooled.

The brick must be sorted in emptying the kiln. The upper courses will be very hard-burned but possibly air-checked. They are excellent for foundations or sewers and are sometimes called sewer brick. From the zone of checked brick to within a few courses of the bottom, the brick should be "No. 1 pavers"; the lower courses have not been sufficiently heated to be vitrified and are classed as "No. 2 pavers." These last ones are excellent building brick.

TERRA COTTA

489. Architectural Terra Cotta. Terra-cotta Lumber, Building Blocks, and Fireproofing. Terra cotta is composed of practically the same material as brick, but requires a carefully selected, finely divided homogenous clay which burns to a desirable color with a slight natural glaze. It is very seldom that a single clay is used in the production of terra cotta as each shade and tint generally requires the mingling of different clays. Fireclays are often used in the manufacture of architectural terra cotta.

The clays after delivery at the factory are ground separately in wash mills or edge-runner mills, mixed with grit and water in pug mills, and deposited in layers or strata. As many as ten or twelve strata are thus piled up, and from this mass perpendicular cuts are taken and the whole mixed together in a pug mill into a plastic mass.

The subsequent manner of molding depends largely upon the kind of ware being made. Terra cotta for architectural purposes is usually made by hand molding in plaster molds. Intricate designs are modeled without a mold, and green casts are often further carved by hand before being dried and burned. After drying and before burning, a coating of "slip" is applied to the ware. This slip is made up of clay, feldspar, flint, etc., is opaque, and imparts the color desired for the finished product. Either a dull or a bright glazed finish may be secured.

Burning is done with extreme care to prevent either distortion or discoloration by flames or gases. Special kilns in which the ware does not come in contact with the gases are needed. Very elaborate designs of high artistic merit are sometimes executed. As it is not practicable to burn terra cotta in very large units, it is often necessary to make a complete design of many comparatively small sections.

Terra-cotta blocks or *terra-cotta lumber* is an entirely different material being made for strictly structural purposes and not at all for decorative effect. It is nearly always covered by plaster or mortar.

The raw materials for terra-cotta lumber are terra-cotta clays and finely cut straw or sawdust. The materials are thoroughly mixed in a mixer or pug mill to form a stiff mud, which is then forced through a die by a plunger-type machine. Practically all terra-cotta lumber is made of hollow construction, with walls about 1 inch thick, and with partitions about ¾ inch thick.

The blocks are wire-cut, like ordinary stiff-mud brick, and are carefully dried before firing. Firing is usually done in a down-draft kiln, and especial care is required in stacking up the ware in such a manner as to prevent distortion and unequal heating. The temperature of burning is sufficient to burn out all the straw or sawdust incorporated in the mix, leaving a very light and porous material which is soft enough to be cut with a saw and into which nails or screws may be driven.

Hollow building blocks and *fireproofing* are the same thing as terra-cotta lumber except that no straw or sawdust is incorporated with the clay and the burning is carried to a higher temperature, almost to vitrification. They are therefore much harder than terra-cotta lumber and are not porous, but resemble ordinary hard-burned brick.

Hollow building blocks are made in the same shapes as terra-cotta lumber and have the same uses. Both are used extensively as a fireproofing material for exterior and partition walls, ceilings, floor arches, furring for outside walls, roof sheathings, and jackets around beams and columns of steel-framed buildings.

490. Roofing Tile. Roofing tile must be hard, strong, and of low absorption. They are made similarly to re-pressed stiff-mud brick, the blanks being formed by an auger machine and subsequently re-pressed. Shingle tile are laid like slate, being perfectly flat; mission style tile are, in a measure, interlocking, being segments of hollow cones; and Spanish tile are distinctly interlocking. The two last forms are made by re-pressing slabs of green clay. The clay is selected with greater care than for ordinary brick, and burning is done at a sufficiently high temperature to insure hardness, strength, and low absorption.

491. Wall Tile. Wall tile are of two general types, according to the process of fabrication.

Dust-pressed Tile. The clay for making dust-pressed tile may be a fireclay, a shale clay, or a mixture of white clays, feldspar, flint, etc. These materials after grinding and mixing are made up into a thin cream which is strained through a fine screen. The water is then drained or squeezed out and the material dried, crushed to powder, moistened slightly by steam, and stored until used. Molding is done in a dry press, and any desired relief pattern is imprinted by the moving plunger of the press. The ware is now placed in fireclay boxes in which it is burned out of contact with the flames. After burning, a transparent or opaque glaze is applied, coloring matter being introduced if desired. A second firing is now required to fuse the glaze. Either a bright or a dull glaze is obtained by proper selection and application of the glaze materials.

Plastic tile are made in practically the same manner as "dust-pressed" tile, except that a mixture of soft clay and powdered burned clay is used, and the molding is done immediately after mixing and tempering. Molding is done by hand in plaster molds which may or may not impart a design to the face. In the latter case the tile may be removed from the mold when partly dry and a design modeled by hand. If plastic tile are not glazed, no second firing is required. Most wall tile are dust-pressed tile.

492. Floor Tile. Floor tile are dry-pressed from the same materials as wall tile, and the process is practically the same. Fireclays and red-burning clays are most commonly used, however, and with white-burning materials coloring matter is usually introduced. No glaze is used and only one firing is necessary.

493. Drain Tile. Drain tile are made from a red-burning clay or mixture of clays like those used in making terra-cotta lumber. The clay is handled by the stiff-mud process, issuing from a special die as a hollow cylinder, which is cut to convenient lengths by wires. Burning is conducted at temperatures necessary to produce a very porous tile, which possesses a considerable degree of mechanical strength, but is not vitrified or glazed. Drain tile are intended to take up and carry off the water in wet soil and, therefore, must be porous.

494. Sewer Pipe. Sewer pipe is not meant to be porous or absorptive like drain tile, but on the contrary is made from clays that will form a very non-porous product of low absorption. The stiff-mud process of mixing and molding is used whether the pipes are fitted with socket ends or not. Special shapes, such as elbows, Y's, and T's, are made by joining parts of green pipe with slip clay.

After drying in steam chambers the ware is burned in down-draft kilns. A special "salt glaze" is imparted to all surfaces of the pipe by throwing common salt into the kiln fires after a temperature of about 1150° C. (2102° F.) has been attained. The sodium vapors freed by heat pass through the kiln, and by combination with the clay form a dense, hard glaze, which renders the pipe practically non-absorptive.

Sewer pipes are intended exclusively for use as conductors of water, sewage, etc., and are laid with tight cement joints.

PROPERTIES OF BRICK, TERRA COTTA, AND TILE

495. General. The more important physical properties of brick are: compressive strength, flexural strength, shearing strength, and weather resistance. Of less importance, but still useful, are: absorption, porosity, density, and hardness.

These properties are of much more consequence in application to brick masonry than in individual bricks. The raw materials and the manner and degree of burning influence the physical properties greatly, and, therefore, wide ranges in values are to be expected.

496. Crushing Strength. Since the strength of brick masonry is only a fraction of the strength of the brick, the compressive strength of individual bricks is of only relative value in that it affords a basis of comparison between different kinds of brick. Laminations and other defects are often revealed in the fracture. Bricks are usually tested flatwise as they are more often laid in that manner. The compressive strengths flatwise and edgewise are not often the same, and no definite relation seems to exist between them.

The average compressive strength, in pounds per square inch, of good building brick is about 4000; of pressed brick, about 8000; of sand-lime brick, 3000 to 4000; of paving brick, 10,000; of fireclay brick, 3000 to 6000; of concrete brick, 1500 to 3500; of terra-cotta blocks, 4000; and of architectural terra cotta, 3000.

497. Absorption. The absorption of water by brick is often considered to be indicative of its probable durability. It is sometimes claimed that the freezing of water which fills the pores of brick will constitute a disintegrating agency, but the importance of this factor is overestimated. Bricks are seldom injured by frost for the reason that water does not fill the pores completely and therefore is able to expand upon freezing without exerting any great disruptive force.

Tests of absorptive power of bricks are usually made to extend over so short a period that the results are likely to be misleading. The rate of absorption of bricks varies greatly, and therefore the usual 48-hour test will sometimes show practically the ultimate absorptive power of a brick and other times only a fraction of the ultimate absorption. In another absorption test the bricks are immersed in water at room temperature, brought to a boil in 1 hour, boiled for 5 hours, allowed to cool again to room temperature, and weighed.

In general the absorption shown by common building brick in a 48-hour immersion test or the boiling test is from 12 to 18 per cent of the weight of the dry brick. For pressed or face brick the absorption is about 6 to 12 per cent; for sand-lime brick it is 12 to 15 per cent; for paving brick, 1 to 3 per cent; for fireclay brick, 8 to 12 per cent; for concrete brick, 8 to 15 per cent; and for unglazed building blocks of terra cotta, 10 to 15 per cent.

498. Flexural Strength. The flexural strength of bricks is considered by many authorities to be the best indication of their quality. This test is easily made and furnishes an approximation of the tensile strength by means of the modulus of rupture. Experiments and experience show that the failure of brick masonry under compressive stress is usually caused by failure and subsequent lateral flow of the mortar, thereby producing tensile stresses in the bricks and causing cracks to open up in the masonry. The fractured surface of a brick often affords a valuable indication of the care with which the materials have been ground and mixed, and the degree of burning is made evident to an experienced observer.

The modulus of rupture of common building brick varies from about 500 to about 1000 pounds per square inch; pressed brick, 600 to 1200; sand-lime brick, 300 to 600; paving brick, 1500 to 2500; fireclay brick, 300 to 600; concrete brick, 250 to 500; and unglazed terra-cotta building blocks, 500 to 1000.

499. Shearing Strength. The shearing strength of bricks as shown by tests is a property of little practical importance, chiefly because it is impossible to determine the actual shearing strength. All methods of testing which have been devised are more or less subject to the same objection, i.e., the shearing stress is not acting alone, but bending is introduced, thus bringing tension and compression into play as well as shear. The shearing strength of common brick is about 1000 to 1500 pounds per square inch; pressed brick, 800 to 1200; sand-lime brick, 500 to 1000; paving brick, 1200 to 1800; and fireclay brick, 500 to 1000.

500. Modulus of Elasticity. The modulus of elasticity of bricks is not a constant for any considerable range of loading. The elastic properties, as shown by the stress-strain curve for a compressive test, are quite similar to those of concrete and mortars. For ranges of loading not exceeding one-fourth of the compressive strength the modulus of elasticity of common brick is about 1,500,000 to 2,500,000 pounds per square inch; pressed brick, 2,000,000 to 3,000,000; sand-lime brick, 800,000 to 1,200,000; concrete brick, 2,000,000 to 2,500,000; and paving brick, 4,000,000 to 8,000,000.

501. Efflorescence. Efflorescence is the deposit of crystallized salts on the surface of brick masonry. The most common of these salts is calcium or magnesium sulfate, although potassium and sodium salts are often found. The cause of efflorescence is the presence of these salts in a more or less soluble form in the bricks themselves or in the mortar used in laying them up.

SPECIFIED TESTS AND CLASSIFICATIONS

502. General. Considerable difference of opinion prevails concerning the proper manner of testing brick and the weight to be placed upon the data obtained from the tests. Among the tests that have been suggested are the following: compression wet, compression dry, flexure, absorption, freezing and thawing, and fire resistance. Except where fire resistance is of prime importance, the tests that are usually specified are two or all three of the following: compression dry, flexure, and absorption.

503. Building Brick. The American Society for Testing Materials classifies building brick. The specified requirements for each class of clay and sand-lime building brick are shown in Table XLIV.

TABLE XLIV

A.S.T.M. Classification of Clay and Sand-lime Building Brick

Name of Grade		Compressive Strength (bricks flatwise), lb. per sq. in., mean gross area		Modulus of Rupture (bricks flatwise), lb. per sq. in., gross area	
Clay	Sand-lime	Mean of 5 Tests	Individual Minimum	Mean of 5 Tests	Individual Minimum
A	SW	4500 or over	3500	600 or over	400
B	MW	2500–4500	2000	450 or over	300
C		1250–2500	1000	300 or over	200
	NW	1500–2500	1500	300 or over	200

Note: The above classifications are based on strength and do not necessarily measure weathe resistance.

"The classification of any lot of brick shall be determined by the results of the tests for that requirement in which it is lowest unless otherwise specified."

The specified requirements of the American Society for Testing Materials for concrete building brick are given in Table XLV.

TABLE XLV

A.S.T.M. CLASSIFICATION OF CONCRETE BUILDING BRICK

Class	Compressive Strength (bricks flatwise), lb. per sq. in.		Modulus of Rupture (bricks flatwise), lb. per sq. in.	
	Mean of 5 Tests	Individual Minimum	Mean of 5 Tests	Individual Minimum
Grade B	2250	2000	450 or over	300
Grade C	1250	1000	300 to 450	200

Well-made concrete brick will often show a compressive strength above 3000 pounds per square inch.

504. Paving Brick. Bricks to be used as paving bricks are usually subjected to a standard "rattler" test. In this test a charge of ten bricks of block size is placed in a standard rattler, with an abrasive charge made up of 10 cast-iron balls 3¾ inches in diameter and weighing approximately 7½ pounds each and a sufficient number of cast-iron balls 1⅞ inches in diameter, weighing approximately 0.95 pound, to bring the total weight of the charge to as nearly 300 pounds as possible.

The rattler is rotated at a uniform rate, between 29.5 and 30.5 revolutions per minute, for 1800 revolutions. The loss in weight is calculated in per cent of the initial weight of the brick.

The percentage of loss is not definitely standardized, but Table XLVI shows what may be expected.

TABLE XLVI

LOSSES IN RATTLER TEST OF PAVING BRICK

	General Average Loss, per cent	Maximum Permissible Loss, per cent
For bricks suitable for heavy traffic	22	24
For bricks suitable for medium traffic	24	26
For bricks suitable for light traffic	26	28

A well-made paving brick will show very much less wear than suggested by the above table.

505. Sewer Brick and Sewer Pipe. *Sewer brick* are subjected to the same tests as building brick, and their classification according to the

American Society for Testing Materials is printed in Table XLVII. It will be seen that sewer brick are essentially high-grade building brick, with especially low absorption.

TABLE XLVII

A.S.T.M. CLASSIFICATION OF SEWER BRICK

Class	Absorption Limits, per cent		Compressive Strength (on edge), lb. per sq. in.		Modulus of Rupture, lb. per sq. in.	
	Mean of 5 Tests	Individual Max.	Mean of 5 Tests	Individual Min.	Mean of 5 Tests	Individual Min.
Class A Vitrified	3 or less	....	5000 or over	....	1200 or over	...
Class B Vitrified	5 or less	6.0	5000 or over	4000	1200 or over	800
Hard	5 to 10	12.0	3500 or over	2500	600 or over	400
Medium	10 to 15	17.0	2000 or over	1500	450 or over	300

Sewer pipe, whether clay or cement concrete, is usually subjected to crushing tests, hydrostatic pressure tests, and absorption tests. The crushing strength is usually obtained by the three-edge-bearing method in which the lower bearing consists of two bearing strips placed 1 inch apart and the upper consists of a single bearing strip, all strips extending along the full barrel length of the pipe. The sand-bearing method is sometimes used in which the sewer pipe is bedded, above and below, in sand for one-fourth the circumference of the pipe. The hydrostatic-pressure test consists of completely stopping the two ends and applying the following pressures internally: 5 pounds per square inch for 5 minutes; 10 pounds per square inch for 10 minutes; and 15 pounds per square inch for 15 minutes. The absorption test is conducted on a specimen 12 to 30 square inches in area with broken edges, in a manner similar to the absorption test for building bricks.

The maximum allowable percentage absorption for all sizes of pipe is 8 per cent. The minimum allowable crushing strength by the three-edge-bearing method varies from 1000 pounds per linear foot for 4-inch pipe to 3080 pounds per linear foot for 36-inch pipe. The physical test requirements for clay and cement-concrete sewer pipes are the same. The use of cement-concrete pipes, however, should be avoided wherever the sewage shows an acid reaction.

506. Building Tile and Drain Tile. Standard specifications for three classes of hollow burned-clay building tile—namely, load-bearing wall tile; floor tile; and non-load-bearing tile—as established by the American Society for Testing Materials are given in Table XLVIII. In these specifications the recommended physical tests are compression and absorption, the compression to be applied in the direction in which the tile will be loaded, and the result to be calculated in pounds per square inch of gross area for load-bearing wall tile and net area for floor tile. No strength requirements are stated for non-load-bearing tile which is used for partitions, fireproofing, and furring.

TABLE XLVIII

A.S.T.M. CLASSIFICATION OF BUILDING TILE

Designation of Class	Absorption, per cent		Compressive Strength, lb. per sq. in.			
			End Construction		Side Construction	
	Mean of 5 Tests	Individual Max.	Mean of 5 Tests	Individual Min.	Mean of 5 Tests	Individual Min.
Load-bearing Wall Tile			(Gross Area)			
LBX	5 to 16	19	1400 or more	1000	700 or more	500
LB	5 to 25	28	1000 or more	700	700 or more	500
Floor Tile			(Net Area)			
FT1	5 to 25	25	3200 or more	2250	1600 or more	1100
FT2	5 to 25	25	2000 or more	1400	1200 or more	850
Non-load-bearing Tile						
NB	5 to 25	28	No requirements			

Drain tile are classified by the American Society for Testing Materials as farm, standard, or extra-quality. The farm tile are manufactured in standard diameters of 4 to 15 inches, and the standard and extra-quality tile from 4 to 42 inches with special sizes up to 60 inches. The tiles are further classified according to materials as shale and fireclay tile, surface-clay tile, or concrete tile.

Drain tile are tested for absorption in the same manner as sewer pipe, and for crushing load per linear foot by the two-edge-bearing, three-edge-bearing, or sand-bearing methods. The required strengths for the extra-quality pipe are but slightly higher than those quoted for sewer pipe. The allowable absorption varies from 7 to 14 per cent depending on the classification of the pipe.

BRICK MASONRY

507. General. Brick masonry, for many purposes, compares favorably with most stone masonry; it is cheaper, more easily built, resists fire better, and is very durable.

508. Mortar Joints. Mortar is the plastic mixture of two or more materials, which is used to bind individual bricks together into a solid mass. The proper composition, preparation, and use are as important in producing good masonry as the quality of the brick themselves. Lime mortar is generally used in the construction of brick masonry. The slower-setting magnesian limes are preferred because the brick can be laid faster than with mortar made with high-calcium lime. The common proportions in lime mortars are 1 part lime and 2 or 3 parts sand.

Ordinary lime mortar hardens very slowly, and the gain in strength is too slow when high walls are built rapidly. For such construction Portland cement should constitute a portion of the mortar or, better still, a Portland cement mortar may be used altogether. The proportions of such a mortar are generally 1 part of Portland cement and 3 parts of sand.

For all construction below grade, or in any situation where moisture is encountered, also in heavily stressed brick masonry in piers, arches, etc., cement mortar should always be used instead of lime mortar.

There are many different specifications for brick mortar, but the following may be considered typical:

A. Lime Mortar.
  1 part of lime putty or dry hydrated lime to not over 3 parts of sand by volume.
B. Lime-cement Mortar.
  1 part of lime putty or dry hydrated lime, 1 part of Portland cement, 6 parts of sand by volume.
C. Cement Mortar.
  1 part of Portland cement, 3 parts of sand by volume with an allowable addition of lime putty or dry hydrated lime not exceeding 15 per cent of the volume of the cement.

All brick should be laid with the minimum thickness of joints consistent with proper bedding. Common brick are usually somewhat rough and uneven, but should be laid with joints from 3/16 to 3/8 inch in thickness. It is commonly specified that the height of eight courses of brick masonry shall not exceed the height of eight bricks laid dry by more than 2 inches.

Pressed brick, being usually smooth and true, are laid with joints not exceeding 1/8 or 3/16 inch in thickness.

509. Bond. Bond in brickwork is the arrangement of the bricks in courses, resorted to for the purpose of tying together all parts of walls more than one brick in thickness by the action of the weight of the overlying masonry. The commonly adopted bonds for laying brick masonry are *common, English,* and *Flemish bonds.*

In common bond, Fig. 124, all the outside bricks are laid as stretchers for four to six courses, and then a course of headers is placed. This type of bond is more generally used than any other in this country.

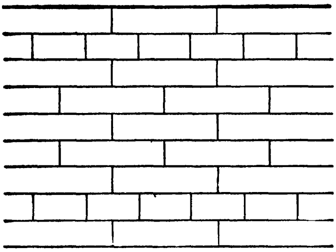

FIG. 124.—Common Bond of Brickwork.

In English bond, Fig. 125, heading and stretching courses alternate. This is the strongest type of bond, but has not a pleasing appearance.

In Flemish bond, Fig. 126, headers and stretchers alternate in each course, each header being centrally placed with respect to a stretcher in the course below. This is a strong bond, but requires cutting brick for each course at corners.

Mortar, unless very wet, does not adhere to dry brick nor does it set properly, for the reason that the water in the mortar is absorbed by the bricks. All bricks should therefore be wet before being laid.

510. Strength of Brick Masonry. The appearance and durability of brick masonry are usually of more importance than the actual crushing strength of piers themselves, but occasionally, in arches and in the lower portion of the walls of high buildings built without a steel or concrete frame, the stresses encountered may be sufficiently high to make the crushing strength of the brickwork an important consideration.

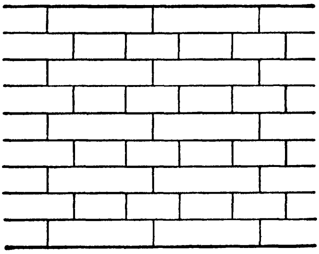

FIG. 125.—English Bond of Brickwork.

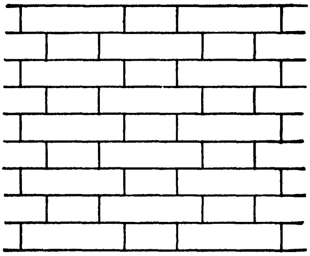

FIG. 126.—Flemish Bond of Brickwork.

The strength of brick masonry is always more a function of the mortar, the bond, and the workmanship than of the strength of the individual bricks. Where high stresses are encountered cement mortar is required, particularly if a heavy load must be carried within a short time after the masonry is laid.

The tests given in Table XLIX comprise a summary of tests of 24 brick piers about 12 inches square and 8 feet high made at the Watertown Arsenal.

These tests show the importance of using cement mortar in preference to lime mortar where strength is an important consideration. The strength of the 1 : 3 cement mortar masonry is approximately twice that of the lime mortar masonry, while little is gained by the use of neat cement instead of 1 : 3 cement mortar except in piers built with the highest-quality bricks where the mortar of neat cement develops a greater proportion of the strength of the bricks.

TABLE XLIX

CRUSHING STRENGTH OF BRICK PIERS

WATERTOWN ARSENAL TESTS, 1904

Age 6 months

Description of Brick	Compressive Strength, lb. per sq. in.			Per Cent of the Average Crushing Strength of Brick		
	Neat Port.	1 Port., 3 Sand	1 Lime, 3 Sand	Neat Port.	1 Port., 3 Sand	1 Lime, 3 Sand
Face Brick						
Dry-pressed face......	2880 [1]	2400	1517	26	21	13
Re-pressed mud......	1925	1670	1260	28	25	19
Common Brick						
Wire-cut stiff-mud....	4021	2410 [1]	1420	31	19	11
Hard sand-struck.....	4700 [1]	1800 [1]	994	42	16	9
Hard sand-struck.....	1969	1800	733	44	40	16
Hard sand-struck.....	1400	1411	718	24	24	12
Light-hard sand-struck	1510 [1]	1519	732	23	23	11
Light-hard sand-struck	1061	1224	465 [1]	20	23	9

[1] Tested at age of 1 month.

From tests made upon bricks and brick masonry by McBurney * the following conclusions are drawn:

1. The various measures of the strength of brick, compressive, flatwise and on edge, transverse, tensile and shearing, vary in their relation one to another for different makes of brick.

2. The factors, workmanship, strength of mortar, types of construction, and regularity of size and shape of brick being equal, compressive strength of brick,

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* J. W. McBurney: Bureau of Standards, Washington, D. C.

flatwise, is the most consistent measure of compressive strength of brick masonry.

3. For the soft-mud and dry-pressed brick the ratios of compressive strength flatwise to transverse strength are fairly constant. The transverse strength of these bricks is as good a measure of wall strength as the compressive flatwise strength.
4. The ratio, wall strength to brick strength, varies with variation in workmanship, strength of mortar, type of construction, and regularity of size and shape of brick.
5. Where there is a difference in strength between bricks, the ratio of wall strength to brick strength for the stronger brick is more affected by change of mortar strength than the corresponding ratio for the weaker brick.
6. All other factors being equal, the brick most regular in size and with plane, parallel faces, will give the highest masonry strength.
7. The ratio, strength at first crack to maximum strength of masonry, seems influenced especially by the ratio of transverse to compressive strength and the regularity in size and shape of the bricks.

There is no recognized specification for the shape and size of brick masonry piers used in determining the compressive strength of brick masonry, but if the ratio of height to thickness, $\frac{h}{t}$, of piers is 6 or greater, the effect of shape upon the stresses obtained by test will be largely eliminated. Krefeld * has reported the strength correction factors given in Table L from results of tests made upon 8- by 16-inch and 12- by 16-inch piers of various heights:

TABLE L

STRENGTH CORRECTION FACTORS FOR BRICK MASONRY PRISMS

Ratio, Height to Thickness	Strength Correction Factor	Ratio, Height to Thickness	Strength Correction Factor
1.1	0.45	5.0	0.96
1.5	0.59	6.0	1.00
2.0	0.67	8.0	1.03
2.5	0.75	10.0	1.06
3.0	0.80	12.0	1.09
4.0	0.89		

511. Hollow Brick Walls. Air spaces are frequently provided in brick walls to provide insulation and decrease absorption of moisture. One method consists of building hollow brick walls with a 4-inch wall on the outside, an 8-inch bearing wall on the inside, and a 2-inch air space between them. In cheaper construction the bricks may be placed on edge, reducing the wall thickness to about 8 inches. Common, English, and Flemish bonds can all be employed in modified form when the bricks are laid on edge.

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* W. J. Krefeld: *Proc. Am. Soc. Test. Mats.*, v. 38, Part I, 1938.

512. Reinforced Brick Masonry. Reinforced brick masonry consists of bricks, mortar, and steel reinforcement, the reinforcement rods being placed in the mortar in proper position in the structure so as to resist tensile stresses. The steel bars are placed horizontally in beams and lintels and both horizontally and vertically in walls. The addition of steel reinforcement develops flexural strength and resistance to lateral loads. Tests have indicated that adequate bond strength between steel and mortar and between bricks and mortar exists when good construction methods are employed.

A variety of structures have been built with reinforced brick masonry including arch bridges, walls, columns, floor slabs, porch floors and steps, stairways both plain and spiral, retaining walls, faces of dams, and structures of circular plan such as silos and storage bins. Reinforced brick masonry is more costly than reinforced concrete but is sometimes selected where appearance is a factor.

GLASS BUILDING BLOCKS

513. General. Glass building blocks will be discussed at this point since they are frequently employed in connection with masonry construction. Glass building blocks are inserted in walls and partitions to transmit light. They are not used to withstand load in bearing walls.

514. Manufacture. Glass building blocks are manufactured by a process which causes a partial vacuum to be produced in the interior of the blocks. The glass is $\frac{1}{4}$ inch or more thick. After being formed, the glass blocks are annealed.

The top and bottom outside surfaces and the ends frequently have a rough surfacing material bonded to the glass for the purpose of obtaining good adherence with mortar. The outside side surfaces of the glass block may be smooth or molded with vertical ribs. The inside side surfaces have either horizontal or vertical ribs in the glass; the selection of the type of inside ribs is dependent upon the light source.

515. Physical Properties. Glass building blocks have hard surfaces and hence are not acoustical materials. Although the blocks transmit light they are not transparent and hence have the advantage of giving privacy to interior rooms. They have exhibited good fire resistance under test.

516. Construction Practice. Glass building blocks are laid with a $\frac{1}{4}$-inch mortar joint. A 1 part Portland cement, 1 part lime, and 4 parts sand mortar of stiff consistency is generally used. The blocks do not absorb moisture from the mortar. Cork or special cement is placed in the joints on top of panels and at sides near bottom of panels to reduce stresses in glass blocks. Panels of glass building blocks up to 144 square feet of surface area with no side longer than 20 feet are typical of good practice.

QUESTIONS

1. What are the requirements for a good brick-making clay?

2. Name and describe three processes of manufacturing structural clay products.

3. What is "de-airing," and what are its advantages?

4. Describe the essential features involved in drying structural clay products.

5. Describe the four stages of burning structural clay products.

6. Describe the different types of brick kilns.

7. Distinguish between the following bricks: salmon brick, arch brick, vitrified brick, face brick, glazed brick, enameled brick, vertical fiber paving brick, and re-pressed paving brick.

8. Describe the manufacture of sand-lime brick.

9. Distinguish between terra cotta and terra-cotta lumber.

10. Distinguish between drain tile and sewer pipe.

11. How is the glaze on sewer pipe obtained?

12. What is efflorescence?

13. Compare building brick and paving brick with respect to: character of raw materials, temperature of burning, and structural strength.

14. Assuming that you are called upon to pass upon the acceptability of a given grade of building brick for a certain purpose and that you have available laboratory facilities for making tests, name and briefly describe the tests that you would make, including both superficial examinations and laboratory tests.

15. Discuss the significance of the absorption test of brick, and state what percentages of absorption are permissible in various kinds and grades of bricks.

16. What are the requirements specified for Class A clay building brick?

17. What is the three-edge-bearing method of testing pipes?

18. Name and describe three types of bond for brickwork. What are the advantages of each type?

19. List the advantages and disadvantages of the following materials for the bonding cement in the mortar for a brick building: gypsum plaster, quicklime, hydrated lime, slag cement, and Portland cement.

20. Upon what factors does the strength of brick masonry depend?

21. What is the purpose of placing reinforcement in brick masonry?

22. Describe the use of glass building blocks in building construction.

23. What are the reasons for facing a reinforced-concrete type of building with brick?

24. A builder has the choice among the following materials for the exterior walls of a house: building brick, sand-lime brick, natural limestone, natural sandstone with iron oxide cementing material, and wood. List the advantages and disadvantages of each of these materials for such a purpose.

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CHAPTER XIX

REFRACTORY AND HEAT-INSULATING MATERIALS

By Gordon B. Wilkes *

Edited by Lloyd F. Rader

REFRACTORY MATERIALS

517. General. The term refractory is applied to materials that are commonly used in the construction of furnaces, flues, crucibles, pyrometer tubes, etc. There are two main requirements for a refractory material: first the ability to withstand high temperatures; and second, the possession of suitable physical and chemical characteristics to withstand hot gases, abrasion, slag action, sudden changes of temperature, flue dust, etc.

518. Classification of Refractories. The *acid refractories* include all the fireclay mixtures which constitute approximately 80 per cent of the refractory products, and all the silica brick and shapes.

The *basic refractories* include the bauxite (high-alumina), lime, magnesite, and zirconia materials.

The *neutral refractories* are represented by the chromite, carbon, and silicon carbide materials.

519. Firebrick Manufacture. *Fireclay Brick.* Raw fireclays may be roughly divided into two classes: (1) flint clay, which has a hard structure, is slowly affected by water, has no binding qualities and a fairly high fusion temperature; (2) plastic clay, which has a soft structure, breaks down readily upon exposure to weather, has some binding quality and generally a fusion temperature somewhat lower than the flint clays.

Table LI from Ries' "Economic Geology" compares the composition of fireclays and typical brick clays.

The raw clays are mixed and crushed to size, and, generally, calcined material (grog) is added in order to reduce the shrinkage during burning. There is some hand molding, especially of intricate shapes, but the large percentage of standard firebrick are machine molded.

Before placing the fireclay materials in the kilns, they are usually dried, sometimes by means of a very slow floor drying at a relatively low

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TABLE LI

COMPOSITION OF FIRECLAYS AND BRICK CLAYS

Material	SiO_2	Al_2O_3	Fe_2O_3	FeO	CaO	MgO	Alk.	H_2O	CO_2	SO_3
Plastic fireclay	57.62	24.00	1.90	1.20	0.70	0.30	0.70	13.20	.....	0.35
Flint fireclay	59.92	27.56	1.03	....	Tr.	Tr.	0.64	10.82	.....	....
Brick shale	54.64	14.62	5.69	....	5.16	2.90	5.89	4.59	4.80	....
Calcareous brick clay	38.07	9.46	2.70	....	15.84	8.50	2.76	2.49	20.46	....
Blue shale clay	47.92	14.40	3.60	....	12.30	1.08	2.70	4.85	9.50	1.44

temperature but more frequently by means of a tunnel dryer heated by the gases from the kilns to a temperature of approximately 121° C. (250° F.).

Fireclay brick is usually burned in circular or rectangular down-draft kilns, but the larger producers are changing over to some type of tunnel kiln which burns the brick more uniformly and more quickly than the down-draft kiln. The burning temperature for firebrick is usually between 1149° C. (2100° F.) and 1371° C. (2500° F.), but in some special instances they are fired to 1621° C. (3000° F.).

Silica Brick. Silica brick are made, ordinarily, by crushing ganister, which is practically pure silica, and adding approximately 2 per cent of lime as a binding material. The bricks are molded either by hand or machine, dried, and fired to a temperature of 1483° C. (2700° F.). Silica brick have a very large coefficient of expansion over a portion of the temperature scale as well as a considerable permanent expansion during firing. Great care must therefore be exercised in the control of temperature during firing as well as in service. Their chief use has been found in the steel industry and by-product coke ovens.

Magnesite brick consist essentially of magnesium oxide with approximately 15 per cent of other oxides. They are used primarily in the basic open-hearth process for the manufacture of steel and in various metallurgical processes.

Bauxite brick are high-alumina brick containing from 55 to 95 per cent aluminum oxide, the remainder being chiefly silica.

Chrome brick contain from 35 to 45 per cent of chromic oxide, the remainder being mainly oxides of magnesium, aluminum, and silicon.

Silicon carbide brick are an electric-furnace product consisting of 85 to 95 per cent of silicon carbide.

Spinel is a special refractory produced in an electric furnace consisting of magnesia and alumina in proportions of the formula, $MgO \cdot Al_2O_3$.

Zirconia (ZrO_2) and *zircon* ($ZrSiO_4$) are two compounds of zirconium that are sometimes used as special refractories.

520. Tests for Refractories. Four tests for fireclay brick have become practically standardized by the American Society for Testing Materials.

Fusion test is carried out by making small cones of the refractory and heating at a specified rate until they soften and bend over, the temperature at which this occurs being noted with an optical pyrometer or with the aid of pyrometric cones. This test is of considerable aid to the manufacturer of bricks but is of doubtful value to the consumer.

Load test consists of heating full-sized brick on end with a load of 25 pounds per square inch applied to the end of the brick. The percentage change in length after being held at a specified temperature for 1½ hours serves as a measure of the load-carrying capacity at high temperatures.

Reheat test consists of heating full-sized bricks for 5 hours at 1400° C. (2552° F.) and measuring the change in dimensions. This test will indicate the permanent shrinkage or expansion to be expected from the bricks when placed in a furnace. If the bricks are to be used at much higher temperatures, it would be advisable to run reheat tests at corresponding temperatures.

Spalling test consists of rapidly heating and cooling the ends of full-sized bricks in order to estimate the resistance of the brick to sudden temperature changes. In oil-fired furnaces, spalling, or the breaking off of pieces of brick, is probably responsible for 90 per cent of the failures.

There are numerous other tests that have not been standardized as yet such as slag resistance, thermal expansion, thermal conductivity, etc.

For high-temperature furnace work, it is nearly always advisable to lay the brick with as thin joints as possible. The bricks, therefore, should be uniform in shape and dimensions. A standard firebrick is 9 inches by 4½ inches by 2½ inches, and contracts sometimes specify the permissible variation from this standard.

The cold crushing strength of firebrick is of minor importance, but they should have a strength of at least 1500 pounds per square inch.

The following results were obtained from approximately 60 brands of firebrick that were subjected to laboratory tests in order to determine their relative merits for high-temperature furnace work.

Fusion temperature	1627° C. (2960° F.) to 1816° C. (3300° F.)
1400° C. (2552° F.) reheat test	1.7% shrinkage to 1.8% expansion
2900° F. air spalling test. Cycles required to lose 20%. Average of 5 bricks of each brand	3 to 30+
Temperature of initial shrinkage under 25-pound load test[1]	982° C. (1800° F.) to 1260° C. (2300° F.)
Temperature of 5% compression under 25-pound load test[1]	1204° C. (2200° F.) to 1517° C. (2760° F.)

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[1] This load was similar to the standard load test except that the temperature was uniformly increased until the brick failed instead of maintaining a constant temperature of 1350° C. (2462° F.) for 1¼ hours and measuring the shrinkage.

HEAT-INSULATING MATERIALS

521. General. The chief reason for the use of heat insulation is the conservation of heat but insulation is often required for other purposes.

In many buildings the cold-water pipes are insulated, not for the purpose of saving heat but to prevent condensation of water vapor when the relative humidity is high. The roofs of textile and paper mills are usually insulated for the same reason.

Insulation may serve as a protection for structural steel in order to decrease the fire hazard. Unprotected structural steel will soften in approximately 10 minutes under a severe fire exposure, but if it is suitably protected by insulation the time before failure can be extended to an hour or more.*

An insulated structure is cooler in summer as well as more comfortable in winter than an uninsulated type. The use of insulation will always tend to make a more uniform distribution of temperature regardless of whether it is applied to a building, a furnace, an oven, or a cold-storage room.

Insulation permits the use of the more convenient but more expensive fuels for heating purposes, and it also tends to make more comfortable working conditions around furnaces, kilns, ovens, etc.

522. Classification of Insulating Materials. Insulating materials are generally divided into three main groups in accordance with their ability to withstand temperature, but with any arbitrary grouping of this nature there is bound to be considerable overlapping.

Low-temperature insulation for use below 100° C. (212° F.). Cold storage, hot water, building insulation, etc.

Moderate-temperature insulation for use between 100° C. (212° F.) and 538° C. (1000° F.). Steam pipes, ovens, low-temperature furnaces, etc.

High-temperature insulation for use above 538° C. (1000° F.). Furnaces, kilns, etc.

523. Composition and Uses. *Low-temperature Insulation.* Insulating materials of this type are composed chiefly of organic substances.

Corkboard, consisting of pure compressed cork with no additional binder, and fiber boards, consisting of cellulose fibers and a binder, are representative of the rigid type of low-temperature insulation. These materials can be used as a plaster base and sometimes are substituted for sheathing. The chief objection to fiber boards is that they are ordinarily made only ½ inch thick and two or more layers are needed to secure effective insulation.

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* Fire Tests of Building Columns. Underwriters' Laboratories, Chicago, Ill., 1917-1919

Fibrous material such as eel-grass, treated wood fiber, hair felt, flax, and kapok, held between two layers of paper or cloth, is a common flexible type of insulation.

Mineral or rock wool consisting of mineral fibers produced by blowing steam through molten rock is frequently used as a loose type to fill the space between the studs of a frame building. This material can be used to fairly high temperatures since it is not organic and the melting point is above 982° C. (1800° F.). Rock wool is also applied in the form of rock-wool blanket which is covered with flameproof muslin.

Another rather interesting development in this field of insulation is the use of chopped paper mixed with silicate of soda that is sprayed on the walls with compressed air. Any desirable thickness up to 2 inches may be applied by this method.

Moderate-temperature Insulation. The well-known 85 per cent magnesia, consisting of 15 per cent asbestos fiber and 85 per cent of the light carbonate of magnesia, is used considerably for temperatures under 315° C. (600° F.). Above this temperature mixtures of diatomaceous earth and asbestos are frequently used. Mineral and rock wool are suitable, and there are a considerable number of asbestos cements that serve well for filling irregular openings and surfaces. In general the asbestos cement is not as good an insulator as the molded product and should only be used where one of the molded shapes is impracticable.

High-temperature Insulation. A large number of insulating blocks and bricks composed chiefly of diatomaceous earth and porous clays can be used up to temperatures ranging from 760° C. (1400° F.) to 1482° C. (2700° F.). Above 1482° C. (2700° F.) some type of firebrick or refractory product, such as silica, magnesite, silicon carbide, or zirconia, is required.

The following physical properties should be considered when choosing an insulating material:

524. Coefficient of Thermal Conductivity. This is usually expressed in the English system of units by K_f, which indicates the number of B.t.u. per hour that will pass through an area of 1 square foot, with a thickness of 1 inch, when there is a 1° F. temperature difference between the two surfaces of the material.

$$K_f = \frac{q \times l}{A(t_2 - t_1)}$$

where q = B.t.u. per hour.
l = thickness in inches.
A = area in square feet.
t_2 = temperature of hotter surface, ° F.
t_1 = temperature of cooler surface, ° F.

The coefficient of thermal conductivity should not be confused with the term "conductance," which compares the insulating value of two materials without taking account of the thickness.

$$C = \frac{q}{A(t_2 - t_1)}$$

The term "transmittance" expresses the "overall" resistance to heat flow and includes the two surface resistances.

$$U = \frac{q}{A(t_2 - t_1)}$$

t_2 = temperature of the air on hotter side.
t_1 = temperature of the air on colder side.

TABLE LII

Insulating Materials

Material	Density, lb. per cu. ft.	Thickness, in.	Maximum Safe Temp., ° F.	Conductance	Coefficient Thermal Conductivity
Corkboard	10	1½	212	0.20	0.30
		2	212	0.15	
		3	212	0.10	
Fiber boards	11–20	½	212	0.6–0.8	0.3–0.4
Mineral or rock wool	12–20	3¾	1500	0.08	0.30
Flexible quilts	4–16	½	212	0.6	0.3
		1	212	0.3	
Hairfelt	10–20	1	212	0.3	0.3
85% magnesia	20	1	650	0.5	0.5
Diatomaceous earth	18	1	1200	0.5	0.5
Insulating brick	20–60	2½	1700–2500	0.3–0.8	0.8–2.1
Firebrick	100–130	2½	2600–3000	2.5–3.2	6–8
Wood	35–55	1	212	0.6–1.6	0.6–1.6
Concrete	140	1	...	6–8	6–8
Iron	490	1	...	350	350

The coefficient of thermal conductivity varies with the temperature, usually increasing with increasing temperatures except in metals. The values stated in Table LII are approximate average values, and considerable variation in special cases is to be expected.

525. Water Resistance. In low-temperature work, there is frequently a tendency for water vapor to condense in the walls with a consequent lowering of efficiency of the insulation. The insulating material should be water resistant and should be protected from the infiltration of air, particularly from the warmer side, since air passing through the wall from the colder side to the warmer side is slowly warmed and there is no tendency for condensation of water vapor under such conditions.

526. Fire Resistance. This factor is very important in building construction since many of the insulating materials consist of organic material. Many of the fiber boards are treated with material that renders them somewhat fire retardant.

In addition to the above factors, a suitable insulating material must be able to withstand the temperature and other physical and chemical conditions of the particular situation.

527. Air Spaces. Heat is transferred by radiation, convection, and conduction, but in a vacuum or thermos bottle, conduction and convection are practically eliminated and the radiation loss is reduced to a minimum by silvering two surfaces of the container. The net loss of heat by radiation may be expressed by the following equation:

$$E = e\sigma(T_2^4 - T_1^4)$$

where E = B.t.u. per hour per square foot.
e = surface coefficient for particular material.
σ = a constant = 16.2×10^{-10}.
T_2 = absolute temperature ° F. (460 + ° F.) of warmer surface.
T_1 = absolute temperature ° F. (460 + ° F.) of colder surface.

From this equation it will be seen that radiation increases with the fourth power of the absolute temperature, and consequently, although a thermos bottle is an excellent insulator at relatively low temperatures, it is not effective at high temperatures. At a temperature of 400° C. (752° F.) a good pipe covering is a better insulator than the best thermos bottle.

The coefficient of thermal conductivity of still air at room temperature is approximately one-half that of corkboard, but heat is also transferred by radiation through an air space and the amount of this radiation can be changed very materially by changing the nature of the surface. Still air spaces make fairly effective insulation at low temperatures but are practically useless at very high temperatures.

528. Standard Tests. The most important of the standard tests for determining the resistance to heat transfer of various materials are the following:

Plate Test. This test is used to determine the coefficient of thermal conductivity of materials that come in flat sheet form and is perhaps our most accurate method for this purpose.

*Pipe Cover Test.** This is a test for determining the heat loss from pipes covered with insulation. The coefficient of thermal conductivity may also be determined during this test, but the values are probably not so precise as those from the plate test.

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* A detailed description of these tests may be obtained from the Committee on Heat Transmission, National Research Council, 40 West 40th Street, New York City.

*Box Test.** A guarded box test serves admirably to determine the rate of heat flow through built-up wall sections.

QUESTIONS

1. Name the principal types of refractory bricks.
2. Compare building brick and fireclay brick with respect to: composition of clay, temperature of burning, and structural strength.
3. Name and briefly describe four tests for refractories.
4. A highly refractory material is desired for the lining of a furnace that is to be used in a metallurgical process in which a large amount of silicon is oxidized to form a slag. What materials might be chosen? Why?
5. What refractories are suitable for: (*a*) the roof of an open-hearth furnace, (*b*) the hearth of a basic open-hearth furnace, and (*c*) the lining of an acid Bessemer converter? Give reasons for your answers.
6. What are the chief purposes of insulation?
7. Name and briefly describe the characteristics and uses of typical insulating materials.

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* Ibid.

SECTION 6

TIMBER

CHAPTER XX

TIMBER *

By Irving H. Cowdrey †

Revised by Lloyd F. Rader

529. General. Timber has been one of the primary materials of engineering construction since the earliest times, and, despite the fact that it has been largely superseded by concrete and steel in certain classes of structures, the total consumption of timber for structural and other commercial purposes is steadily increasing.

In spite of the many species of trees (something like six hundred grow in the United States alone), the kinds of timber of great commercial importance are very limited in number. The larger part of all timber used structurally is derived from only twelve distinct groups—those commonly known as *pine, fir, oak, hickory, hemlock, ash, poplar, maple, cypress, spruce, cedar*, and *walnut*. These common group names usually include several species and varieties, which may show quite diverse characteristics and possess, therefore, very different values as timbers of construction.

Any study of the characteristics and properties of woods must include some information concerning trees. The point of view of the engineer need not be that of the botanist, and his study may be confined to the general features, conditions, and manner of growth of a limited number of species of trees; but physical and mechanical properties of timbers are closely dependent upon structure, and structure is dependent not only

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* The data upon which this chapter is based are taken, very largely, from the publications of the U. S. Forest Service and the textbooks of Record and Betts.

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Large timbers dried only by air-seasoning, even though the process is prolonged for several months or even years, seldom lose sufficient moisture to benefit their strength to more than a slight degree. Such timbers, therefore, cannot be safely depended upon to show any greater strength than if they were in the original green condition. The explanation of this fact is that a great part of the moisture which is first evaporated from wood is water which exists only as "free water" in the lumina of vessels and cells, whereas only variation in the moisture content of the walls of the wood elements affects strength in any way.

The degree of moisture at which maximum absorption by the cell walls is reached is called the "fiber-saturation point" of the wood. After this point is reached added moisture does not lessen the strength of wood. At this point, also, wood ceases to swell.

The fiber-saturation point is determined experimentally by tests of the strength of very small specimens covering a large range of moisture content. When further moisture no longer lessens the strength, the fiber-saturation point is reached, Fig. 135. Tiemann found this point for various woods to be approximately 25 per cent.

550. Weight and Strength. The relation between strength and true density (dry) has been carefully studied at the Forest Products Laboratory, and after analysis of the results of many thousand tests the following expressions have been deduced.

$$\text{Air-dry timber:}\quad \text{Modulus of rupture} = 25{,}700 \times (\text{sp. gr.})^{1.25}$$
$$\text{Green timber:}\quad \text{Modulus of rupture} = 17{,}600 \times (\text{sp. gr.})^{1.25}$$

This is in general true regardless of species. Like all empirical formulas, the above are somewhat inexact. The actual data show that mean values for different species and variation in locality may deviate from the calculated value by 30 per cent. This, however, is no greater variation than may be expected from individual specimens taken at random from any lot of commercial timber. Moreover, the above-noted formulas have been derived from tests on small, clear, straight-grained specimens.

Hence it is probable that the values given by the "Green timber" formula will be more in accord with the actual strengths of commercial sticks even though such timber be actually partially seasoned.

551. Rate of Growth and Strength. The average rate of growth of timber is readily computed by counting the annual rings along a radial line and dividing by the length of the line. The indications are that for most species there is a rate of growth which, in a very general way, is associated with the greatest strength. For the species tested this appears to be as follows:

	Rings per Inch
Douglas fir	24
Shortleaf pine	12
Loblolly pine	6
Western hemlock	18
Tamarack	20
Norway pine	18
Redwood	30

552. The Time Factor in Tests of Timber. Timber differs from most other materials in that small variations in the rate of application of load have a more pronounced effect upon the strength and stiffness shown by a specimen under test. If a timber-compression block or beam is loaded rapidly, it will appear to have a higher ultimate strength, and will also appear to be stiffer, than it will if it is loaded less rapidly. This behavior is due to the fact that the deformation lags far behind the load, and if any load is permitted to remain upon a specimen for a sensible time interval the deformation increases, the amount of increase becoming greater for heavier loads. Actual failure appears to be consequent upon the attainment of a certain limiting amount of deformation or strain, rather than a limiting load or stress.

When constant loads amounting to a large fraction of the ultimate strength of timber are sustained for very long periods, the deformation may continue to increase until rupture occurs, even though the stress encountered is far below the ultimate strength of the timber as originally determined. Several series of long-time tests have shown that timbers, loaded either transversely or in compression with loads amounting to 50 to 60 per cent of the ultimate strength determined by rapid loading, will ultimately fail, the time required varying from a few weeks to several months.

This important conclusion may therefore be drawn: The strength of timber under any kind of permanent load is only about one-half its strength as found by short-time tests.

553. Tabulation of Physical Properties of Structural Timbers. Table LIII, showing the physical properties of American timber, has been compiled from the tests of the U. S. Forest Service.

554. Basic Stresses for Clear Wood. Basic stresses for material which is free from defects affecting the strength and which is used in structural sizes under such conditions that no deterioration will occur are given in Table LIV. These stresses are working-stress values for pieces of timber having a strength ratio of 100 per cent. Allowances have been made for the variability of the strength of clear wood and for the effect of long-continued stress, and a factor of safety has been introduced. These basic stresses have been taken from "Wood Handbook," prepared

TABLE LIII[1]

Physical Properties of a Few Important Woods Grown in the United States

Common and Botanical Name	Weight, lb. per cu. ft.		Shrinkage from Green to Oven-dry (in per cent of green volume)	Modulus of Rupture, lb. per sq. in.		Modulus of Elasticity, 1000 lb. per sq. in.		Maximum Crushing Strength, Parallel to Grain, lb. per sq. in.		Compression Perpendicular to Grain, Proportional Limit, lb. per sq. in.		Maximum Shearing Strength, Parallel to Grain, lb. per sq. in.	
	Green	Air-dry[2]		Green	Air-dry	Green	Air-dry	Green	Air-dry	Green	Air-dry	Green	Air-dry
Hardwoods													
Ash, white (*Fraxinius americana*)	48	*42*	13.3	9,600	*15,400*	1,460	*1,770*	3,990	*7,410*	810	*1,410*	1,380	*1,950*
Elm, white (*Ulmus americana*)	54	*35*	14.6	7,200	*11,800*	1,110	*1,340*	2,910	*5,520*	440	*850*	1,000	*1,510*
Hickory, pignut (*Hicoria glabra*)	63	*52*	17.9	11,700	*20,100*	1,650	*2,260*	4,810	*9,190*	1,140	*2,450*	1,370	*2,150*
Maple, red (*Acer rubrum*)	50	*38*	13.1	7,700	*13,400*	1,390	*1,640*	3,280	*6,540*	500	*1,240*	1,150	*1,850*
Maple, sugar (*Acer saccharum*)	56	*44*	14.9	9,400	*15,800*	1,550	*1,830*	4,020	*7,830*	800	*1,810*	1,460	*2,330*
Oak, red (*Quercus borealis*)	63	*44*	13.5	8,300	*14,300*	1,350	*1,820*	3,440	*6,760*	760	*1,250*	1,210	*1,780*
Oak, white (*Quercus alba*)	62	*48*	15.8	8,300	*15,200*	1,250	*1,780*	3,560	*7,440*	830	*1,320*	1,250	*2,000*
Walnut, black (*Juglans nigra*)	58	*38*	11.3	9,500	*14,600*	1,420	*1,680*	4,300	*7,580*	600	*1,250*	1,220	*1,370*
Conifers													
Cedar, western red (*Thuja plicata*)	27	*23*	7.7	5,100	*7,700*	920	*1,120*	2,750	*5,020*	340	*610*	710	*860*
Cypress, southern (*Taxodium distichum*)	51	*32*	10.5	6,600	*10,600*	1,180	*1,440*	3,580	*6,360*	500	*900*	810	*1,000*
Douglas fir (*Pseudotsuga taxifolia*)	38	*34*	11.8	7,600	*11,700*	1,550	*1,920*	3,890	*7,420*	510	*910*	930	*1,140*
Fir, white (*Abies concolor*)	47	*26*	9.4	5,700	*9,300*	1,030	*1,380*	2,710	*5,350*	370	*600*	750	*930*
Hemlock, eastern (*Tsuga canadensis*)	50	*28*	9.7	6,400	*8,900*	1,070	*1,200*	3,080	*5,410*	440	*800*	850	*1,060*
Pine, longleaf (*Pinus palustris*)	55	*41*	12.2	8,700	*14,700*	1,600	*1,990*	4,300	*8,440*	590	*1,190*	1,040	*1,500*
Pine, shortleaf (*Pinus echinata*)	52	*36*	12.3	7,300	*12,800*	1,390	*1,760*	3,430	*7,070*	440	*1,000*	850	*1,310*
Pine, western white (*Pinus monticola*)	35	*27*	11.8	5,200	*9,500*	1,170	*1,510*	2,650	*5,620*	290	*540*	640	*850*
Redwood (second growth) (*Sequoia sempervirens*	42	*24*	7.4	6,100	*8,300*	1,000	*1,120*	3,280	*5,240*	350	*640*	730	*930*
Spruce, Sitka (*Picea sitchensis*)	33	*28*	11.5	5,700	*10,200*	1,230	*1,570*	2,670	*5,610*	340	*710*	760	*1,150*
Spruce, white (*Picea glauca*)	35	*28*	13.7	5,600	*9,800*	1,070	*1,340*	2,570	*5,470*	290	*570*	690	*1,080*
Tamarack (*Larix laricina*)	47	*37*	13.6	7,200	*11,600*	1,240	*1,640*	3,480	*7,160*	480	*990*	860	*1,280*

[1] Compiled from *Bulletin* 479, 1935, U. S. Department of Agriculture.

[2] "Air-dry" lumber contained 12 per cent moisture.

by the Forest Products Laboratory, U. S. Department of Agriculture, in 1935. Multiplication of the basic stresses by the strength ratio or ratios of the grade of lumber give the working stresses for material which is to remain either dry or saturated. Strength ratios for various grades of lumber and also for use under conditions favorable to decay may be found by referring to "Wood Handbook" and to grading rules of various lumber associations.

TABLE LIV

BASIC STRESSES FOR CLEAR MATERIAL [1]

(All values in pounds per square inch and for material continuously dry or continuously wet)

Species	Extreme Fiber in Bending	Modulus of Elasticity	Compression Parallel to Grain [2] $\frac{L}{d} = 10$	Compression Perpendicular to Grain [3]	Maximum Horizontal Shear
Hardwoods					
Ash, commercial white	1866	1,500,000	1466	500	167
Elm, white	1466	1,200,000	1066	250	133
Hickory, true and pecan	2533	1,800,000	2000	600	187
Maple, sugar and black	2000	1,600,000	1600	500	167
Oak, commercial red and white	1866	1,500,000	1333	500	167
Conifers					
Cedar, western red	1200	1,000,000	933	200	106
Cypress, southern	1733	1,200,000	1466	300	133
Douglas fir, coast region	2000	1,600,000	1466	325	120
Fir, commercial white	1466	1,100,000	933	300	93
Hemlock, eastern	1466	1,100,000	933	300	93
Pine, western white, northern white, ponderosa, and sugar	1200	1,000,000	1000	250	113
Pine, Norway	1466	1,200,000	1066	300	113
Pine, southern yellow (longleaf or shortleaf)	2000	1,600,000	1466	325	146
Redwood	1600	1,200,000	1333	250	93
Spruce, red, white and Sitka	1466	1,200,000	1066	250	113
Tamarack	1600	1,300,000	1333	300	126

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[1] Taken from Table 20, "Wood Handbook," 1935, prepared by Forest Products Laboratory, U. S. Department of Agriculture.

[2] L = unsupported length and d = least dimension of cross-section.

[3] For material that is continuously wet take 70 per cent of these values

555. Elastic Properties of Timber. The ratio of compressive strength to modulus of elasticity which is a ratio of strength to stiffness is much greater for timber than for steel, iron, or concrete. Wood has no well-defined yield point, but the proportional limit, or yield strength, is determined as a measure of elastic strength. Table LIII gives typical values. Wood has a high degree of resilience.

Timber members have good resistance to shock. Wood can withstand a large deformation for a comparatively low stress. A unit volume of steel has greater elastic resistance to shock than wood as measured by area under the stress-strain curve, but since a much greater volume of wood is required to resist a given stress, timber members have better elastic shock resistance than steel. Timber members are much better in this respect than cast iron or concrete. Partly on account of these elastic shock-resisting properties timber is extensively used for railroad ties, fence posts, highway guardrail posts, wagon wheels, implement handles, etc. Resistance to complete failure under shock is less for wood than steel but greater than for cast iron and concrete.

DURABILITY, DECAY, AND PRESERVATION OF TIMBER

556. Durability and Decay of Timber.* "The decay of wood is not an inorganic process like rusting of iron or the crumbling of stone, but is due to the activities of low forms of plant life called bacteria and fungi." Bacteria are among the lowest forms of life, often only a single cell which multiplies by division into two cells which in turn divide again. Several such cells united together form a thread or filament of microscopic size. Fungi consist merely of tiny threads, known as mycelia. The action of fungi and bacteria in destroying wood is, so far as is known, about the same.

Susceptibility to decay and comparative resistance to decay vary with different classes of timber. The determining factors are as yet almost unknown. Hardness, density, specific gravity, and strength seem to have no influence one way or the other. Some very hard tropical timbers decay very rapidly; others last very long. Hard, strong oak decays much faster than light, porous cypress; tamarack and hemlock decay rapidly, while cypress and cedar are lasting; elm and birch are short-lived, the locust long-lived, etc.

557. The Preservation of Timber. The simplest way to prolong the life of timber exposed to the attack of fungi is to reduce the moisture content by seasoning. By piling timber so as to permit free access to air all around it, the moisture may be reduced to about 12 to 15 per cent. Of course the climate and the size of the timbers have a great influence upon the rate of seasoning and the total amount of moisture lost.

The moisture content of air-dry wood may be still further reduced by kiln-drying, but the effectiveness of all methods of moisture reduction as a preservative measure must be limited by the fact that timber so dried readily reabsorbs moisture upon being again exposed to dampness, or even ordinary atmospheric conditions, and benefits obtained are only moderate.

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* *U. S. Forest Service, Bulletin* 78.

"By far the best method of checking the growth of fungi, however, is by poisoning their food supply—by injecting poisonous substances into the timber, so changing the organic matter into powerful fungicides." It is a widespread idea that the germs of decay are inherent in the wood, needing only an opportunity for development to bring about its destruction. On the contrary, all wood-destroying agencies start from the outside and may even be excluded by certain paints which merely coat the surface of the timber but which are poisonous enough to prevent the germination of spores.

The first deliberate attempts to preserve timber from decay date back many centuries, when wood was charred to make it more resistant. Later came the period when wood was coated with preservative paints; then came attempts to inject preservatives into the wood.

Of the many antiseptics that have been proposed for the preservation of timber, only four have been largely used with success in the United States. These are *creosotes* (dead oil of coal tar), *zinc chloride, corrosive sublimate* (bichloride of mercury), and *copper sulfate.* At the present time copper sulfate and corrosive sublimate are used to only a slight extent. There are many patented preservatives, known by various names, practically all of which have either creosote or zinc chloride as their base. Creosote has the advantage of insolubility in water, so that it will not wash out of timber; zinc chloride is often preferred for use in comparatively dry situations.

The processes by which preservatives are injected into timber may be divided into two general classes, the *pressure processes* and the *non-pressure processes,* the distinction being only in the fact that in the former force pumps, air compressors, etc., are utilized, whereas in the latter only atmospheric pressure is relied on.

The Pressure Processes. The pressure processes in general provide for some preliminary treatment, after which the preservative is introduced into the cellular spaces by pressure. The pressure varies in different plants, the maximum being between 200 and 250 pounds per square inch.

If it is intended that the cells of the wood shall remain practically filled with the preservative, the preliminary treatment is such that the imprisoned air and water are very largely removed before impregnation. This is accomplished by exposure to steam, followed by vacuum, which more or less completely empties the cells. The timber is then covered with preservative under pressure which fills the cell spaces to a considerable depth.

When it is desired that the preservative shall merely form a film over the inside of the cells, the timber is first exposed to the action of compressed air. Without abatement of pressure, the preservative is then admitted to the treating chamber under a higher pressure and is thus forced into the cells. Upon the removal of the external pressure, the imprisoned and compressed air within the cells expands and forces out a considerable portion of the preserving fluid.

With zinc chloride, a small amount of glue may be added to retard the leaching effect due to moisture.

The Non-pressure Process. In the non-pressure process the heat of the preserving fluid expands the air within the cells. The cooling of the bath or the rapid removal to a cold bath causes a contraction of the air still remaining in the cells, which tends to produce an infiltration of the preservative.

Superficial Treatments. Less efficient but cheaper treatment can be secured by painting the face of the timber with at least two coats of hot creosote or some similar preservative (the *brush method*). The liquid will not penetrate to any great extent, but as long as there remains an unbroken antiseptic zone around the surface the spores of the fungi cannot enter. Thorough air-seasoning before painting is necessary, since otherwise checks may form and provide a means of access to the interior of the timber for the spores of the fungi.

A still less expensive treatment than the brush treatment is the method of dipping the timber in an open vat of the preservative. Usually the timbers are carried through the bath on chain conveyors and remain submerged only a few minutes at most. *Dipping* is not only more economical of time and labor, but also gives better results than the brush method.

558. Effect of Preservative Treatments on the Strength of Timber. The effect of preservative treatments of timber upon strength has been investigated by the Forest Service under the charge of Professor W. K. Hatt.* It appears in general that the strength of treated timber depends, first, on the percentage of moisture remaining in the wood, and second, on whether the wood has been subjected to injuriously high temperatures during the process of steaming and the vacuum treatment. A high degree of steaming is injurious to wood, the limit of safety depending upon the quality of the wood, the degree of seasoning, and the temperature and duration of the steam bath. During steaming the amount of moisture in the wood must be increased, with consequent weakening of the fibers if the vacuum following the steam is not able to remove the added moisture. There seems to be no ground for believing that non-pressure processes can be injurious to the strength of the timber.

The presence of creosote in itself will not weaken wood, since it appears not to enter the cell walls and fibers, but only to coat them, and so, if the wood is not perfectly seasoned, the temperature of the bath may aid the seasoning and increase the strength of the wood.

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* *U. S. Forest Service, Circular* 39.

The presence of zinc chloride will not weaken wood except by the addition of water by reason of the fact that it is in itself a water solution. Subsequent seasoning will obviate this difficulty. A too-concentrated solution may cause chemical dissolution of some of the wood fibers, but this danger can easily be avoided.

559. Termites. Termites attack timber by eating out the interior of the wood and leaving a shell of sound wood to conceal their activities. Owing to their superficial resemblance to ants in size, general appearance, and habit of living in colonies, termites are frequently called "white ants." There are many species of termites, but from the standpoint of their method of attack on wood the termites of the United States may be classified into two groups: (1) the ground-inhabiting or subterranean termites; and (2) the dry-wood termites. Subterranean termites are found in nearly every state and are responsible for most of the termite damage; dry-wood termites are found only around the southern edge of the United States from central California to Virginia.

Subterranean termites develop their colonies and maintain their headquarters in the ground, from which they build tunnels through earth and around obstructions to obtain the wood they need for food. In order to live, these termites must have a constant source of moisture. Subterranean termites do not establish themselves in buildings by being carried into them in lumber, but by entering from ground nests after the building has been constructed. The damage may proceed so far as to cause collapse of portions of the structure before they are discovered.

Very few woods offer any marked degree of resistance to termite attack. Impregnation with an effective preservative increases resistance. The best protection against subterranean termites is to build so as to prevent their access to the building. The foundations should be of concrete or other solid material through which the termites cannot penetrate. Cement mortar should be used with brick, stone, or concrete blocks because termites can work through some other kinds of mortar. Untreated wood must be kept well away from the ground. Termite shields consisting of sheets of metal that extend out from the foundation at an angle of 45° for a horizontal distance of at least 2 inches should be placed between foundation and woodwork in order to prevent the termites from extending their tubes over the foundation to reach the sills. Metal shields should also be fitted tightly around water and sewer pipes and electrical conduits along which termites could build their tubes and gain entrance to woodwork. Buildings infested with subterranean termites should have the infested wood replaced, preferably with treated wood, and the precautions suggested above for new buildings should be put into effect. The entrance galleries of the termites should be destroyed, and a chemical, such as orthodichlorobenzene, may be poured into a trench near the nests and then covered up with earth so that the termites will be killed by the fumes.

Dry-wood termites can live in dry wood without outside moisture or contact with the ground. They can riddle timbers with their tunnelings if allowed to work unmolested for a few years. Outdoor timbers may be protected by preservative treatment. In constructing a building in localities where dry-wood termites are prevalent, the lumber should be inspected to see that it has not become infested before arrival at the building site. If the building is constructed during the swarming season, the lumber should be watched during the course of construction, since infestation by colonizing pairs can easily take place at this season. Since paint is a good protection against the entrance of dry-wood termites, all exposed wood should be kept adequately painted. Fine screen should be placed over openings through which access might be gained to the interior unpainted parts of the building. Badly infested wood should be replaced; if only slightly damaged, further activity may be arrested by blowing finely divided Paris green, arsenical dust, or sodium fluosilicate into each nest.

560. Marine Borers. Damage to timber structures in sea water and even sometimes in fresh water may be caused by marine boring organisms. Rapidity of attack is dependent on the local conditions and the kinds of borers present. Attack is rapid along the Pacific, Gulf, and South Atlantic coasts of the United States. The principal marine borers encountered in the waters of the United States are the *teredo* and *limnoria.*

The teredo is a small mollusk and, in its early stages, a free-swimming organism. When it lodges on a suitable timber, it bores into the wood by means of a pair of boring shells on the head which grows rapidly in size during the boring process while the tail remains at the surface. The teredo bores into the interior of a timber in a direction normal to the surface and then usually turns at right angles to bore longitudinally, sometimes to a length of several feet. This organism lives upon the wood borings and upon the organic matter extracted from sea water which is pumped through its system. It lines its burrow with a shell-like deposit. The entrance holes do not grow large; the interior of a pile may be completely honeycombed even though the surface shows only slight perforations. An example of damage done by the teredo is shown in Fig. 136.

Limnoria are crustaceans that bore small burrows in the surface of piling. When great numbers are present, their burrows are separated by very thin walls of wood that are easily eroded by the motion of the water and objects floating upon it. This erosion causes the limnoria to bore continually deeper. Since erosion is greatest between tide levels, piling attacked by limnoria characteristically wears within such levels to an hour-glass shape. Untreated piling can be destroyed by limnoria within a year in heavily infested harbors.

Other marine borers which are frequently encountered are (1) *bankia,* which are mollusks similar to the teredo in appearance and action; and (2) *martesia,* which are wood-boring mollusks resembling clams in appearance that are active in the Gulf of Mexico and are capable of doing considerable damage by boring holes up to 1 inch in diameter and 2½ inches in length. *Sphaeroma* are similar to limnoria but are larger and do less damage; they occasionally work in fresh water.

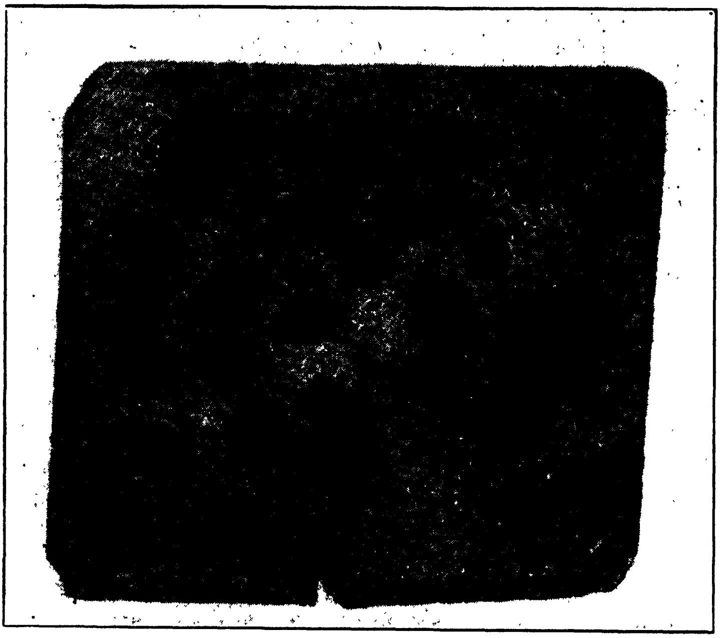

FIG. 136.—Section of Lobster Pot Buoy Attacked by Teredo at Plymouth, Mass., in 1935. (Courtesy of Wm. F. Clapp.)

All woods are subject to marine-borer attack. All commercially important woods of the United States should be protected in any important permanent structure where borers are active. The best practical protection for piling in sea water is heavy treatment with creosote. The treatment should be thorough with deep penetration and high absorption of the creosote in order to obtain satisfactory results in heavily infested waters. Good results may be obtained by forcing in all the creosote the piling can be made to hold by means of the pressure process. The piling should be air-seasoned before treatment.

Limnoria, martesia, and sphaeroma are not always stopped even by thorough creosote treatment. The average life of well-creosoted structures is many times the average life that could be obtained from untreated structures; nevertheless, well-creosoted structures are sometimes damaged seriously.

Shallow or erratic penetration affords but slight protection. The poorly protected spots are attacked, and from them the borers spread inward and destroy the untreated interior of the pile. Low absorption also fails to make the wood sufficiently poisonous to keep the borers out or to provide a reservoir of surplus oil to compensate for depletion by evaporation and leaching. When wood is to be used in salt water, no cutting or injury of any kind should be permitted in the under-water part of the pile.

Protection against borers may be provided by surrounding treated piling by a jacket of concrete, or by clay, concrete, or cast-iron pipe sections. The pipe sections should extend from above high tide to below the mud line, and the space between the wood and the pipe should be filled with concrete.

Paint and batten methods of pile protection vary as to details but consist substantially in: (1) coating the untreated pile with a thick, viscous paint which may or may not contain poisonous materials; (2) applying burlap, roofing felt, or similar material over the paint; (3) applying a second coat of paint; (4) nailing in place a close-fitting layer of narrow battens, which are strips of sawed lumber; and (5) applying a final coat of paint to fill the crevices between the battens and coat the surface thoroughly. Experience has shown that only moderate extension of life can be expected from such treatment. Many attempts have been made to protect piling by sheathing it with sheet copper, Muntz metal, or other corrosion-resistant metal, but they have not generally been successful. As long as a complete covering of metal can be maintained the borers cannot get in, but complete avoidance of damage to the coating has usually been found impractical.

GLUE—VENEER—PLYWOOD

561. General. To the engineer, the use of glue with wood is analogous to the welding, brazing, or soldering of metals. Usually, however, the latter processes are merely for the purpose of uniting parts of a fabricated member, whereas when glue is used with wood it may serve such a purpose or a wholly new product may result, in which the properties of the original wood appear greatly modified, as in plywood.

562. Classification. Glues may be classified in accordance with their source as:

Animal glues, fish glue, albumin glues (blood or egg), casein glue, and vegetable glues.

To the woodworking industries in general, the animal glues are best known and the technique of their application is best understood. They are obtained from hides, hoofs, bones, and certain other slaughterhouse wastes by boiling in water. Each source yields its characteristic glue, and the slightest variation in the details of manufacture exerts a great influence on the finished product. These almost intangible factors make glue a very difficult subject to study from a strict engineering viewpoint as results of tests are often very inconsistent, and specifications are of uncertain value.

The source of fish glue is obvious from the name. This glue is always placed on the market in a liquid form; it is of very little importance to the engineer.

Vegetable glues also are of very little engineering value.

Albumin for glue may be produced either from the whites of eggs or the serum of blood. Blood serum is produced by gravitational separation from the fibrin. From these two prime sources the albumin is ordinarily obtained by means of a centrifuge. The albumin so obtained is mixed with lime and ammonia at the time the glue is to be prepared for use. The various formulas are jealously guarded by the trade.

Casein for glues is obtained from skimmed milk in which the first step is that of curdling. This curdling may be allowed to take place spontaneously by the naturally formed lactic acid, or it may be produced artificially by means of rennet or a weak acid. For the production of a casein glue, the casein is mixed with calcium hydroxide and silicate of soda, all materials dry and finely ground.

563. Preparation and Precautions. Hide glues (the best of the animal glues) are obtained in sheets, flakes, or granulated form. The dry material is soaked in about two and one-fourth times its own weight of water, although the water may be somewhat varied dependent upon the strength it is desired to develop. When the glue is softened, which usually requires several hours, it is melted on a water bath the temperature of which must be carefully controlled and never carried above 150° F. In places demanding the maximum strength, such as airplane construction, it is advisable to use the glue within 4 hours from the time of melting. For best results this kind of glue should never be allowed to cool and then be remelted.

Blood albumin has been used much more in European and Asiatic countries than in America. Its preparation is simple, requiring only the addition of cold water in accordance with the manufacturer's instructions.

Casein glues are similarly mixed with cold water and applied without further preparation. These glues should never be mixed in copper, brass, or aluminum containers.

The strength of a glued joint is a composite function of many variables, some of which are very difficult of control. With the animal glues the temperatures of the room and of the wood are important as well as the temperature of the glue. If small pieces of wood and small areas are to be covered by the glue it is not necessary to preheat the wood, but where the conditions are such that there is danger of chilling the glue before the joint is completed, preheating is necessary. Large work is sometimes clamped between heated metal plates in order that the temperature shall not drop too rapidly. A joint made with animal glue should generally be kept under pressure for at least 12 hours.

Casein glues are applied cold, hence no bad effect is produced by the chilling of the wood. The glue can be applied more deliberately, and there is an actual improvement of the glue strength with the increasing viscosity which appears as the glue stands after mixing. These facts permit work to be done with these glues under much more comfortable working conditions than are possible when using animal glues. Joints formed with casein glues are generally strong enough for machining at the end of 6 hours.

564. General Properties of Glues. The general properties and peculiarities of glues for engineering purposes are summarized in Table LV which is reprinted from *Technical Bulletin* 205 issued by the U. S. Department of Agriculture.

565. Laminated Construction. Glued joints are most commonly formed between the faces, surfaces, or edges of component parts. In such a position the glue film is stronger than the cohesion between the wood cells and fibers immediately adjacent to it. Separation of the component members of such a glued composite is often effected by tearing apart of the wood fibers rather than an actual rupture of the glue film. This fact has given rise to some absurd notions as to the strength of laminated members. The mere sawing of a wooden member followed by regluing will not, in general, increase its strength under any type of load. If the sawing operation has removed defective wood, knots, shakes, or other imperfections, and only the selected material used in the reconstructed member, the laminated member, being freed from the defects, will be stronger than the defective material from which it has been fabricated. Again if the original material contains serious diagonal or spiral grain it may be possible to saw and recombine the layers in such a manner that the inclination of grain will be reversed in the adjacent layers. This process again may be expected to produce a laminated member stronger than the wood from which it has been made. If the layers are very thin (less than $1/16$ inch) and the wood of very open grain, it may be possible to cause the glue to penetrate so deeply that its strengthening effect will be evident through the entire mass of the reconstructed material. In every instance previously mentioned, the

TABLE LV

Properties and Characteristics of Different Classes of Woodworking Glues Used in Aircraft

Property or Characteristic	Casein Glue	Blood-albumin Glue	Animal Glue (untreated)
Strength (dry)	Very high to medium	Medium to low	Very high
Strength (wet after soaking in water 48 hours)	About 25 to 50 per cent of dry strength; varies with glue	About 50 to nearly 100 per cent of dry strength	Very low
Durability in 100 per cent relative humidity or prolonged soaking in water	Deteriorates eventually; rate varies with glue	Deteriorates slowly but usually completely in time	Deteriorates quickly
Rate of setting	Rapid	Very rapid with heat	Rapid
Working life	Few to several hours	Several hours to a few days	Few hours to several days
Consistency	Medium to thick	Variable, thin to thick, depending on formula	Variable from thin to very thick with temperature changes
Temperature requirements	Used at ordinary room temperatures	Heat required to set glues; cold press formula an exception	Control important for glue, wood, and room
Mixing and application	Mixed with cold water; applied cold by hand or mechanical spreaders	Mixed with cold water; applied cold by hand or mechanical spreaders	Soaked in water and melted; applied warm by hand or mechanical spreaders
Tendency to foam	Slight to medium	Slight to pronounced	Usually slight
Tendency to stain wood	Marked with some woods	None, except that dark blue may show through thin veneer	None to very slight
Dulling effect on tools	Moderate to pronounced	Slight	Moderate

fabricated material will be heavier than the original wood. The use of glue, however, permits the fabrication of hollow construction which, when properly designed, combines great strength with small weight.

566. Veneer. This term is applied to thin sheets of wood which may vary in thickness from 0.01 or 0.02 up to about 0.5 inch. They are cut by means of special machines which may use either a saw or a knife. The veneer saw is a circular saw of special form with a cutting edge about 0.05 inch thick. One face is made plane while the other is convexed to give a thickness at the center necessary for the proper stiffness. The veneer saw is efficient only for cutting moderately thick veneers and even then its use is generally limited to the working of the less valuable woods. Sawed veneer is equally firm and strong on both sides of the sheet, and either side may be glued or exposed to view with similar results.

Sliced veneer is cut in the form of long strips by moving a block of wood or "flitch" against a heavy knife. The veneer is forced abruptly away from the block by the knife, thus causing fine checks on the knife side. The checked or "open" side is likely to show defects in finishing and therefore it should be the glue side whenever possible. By this method either "slash" or "quartered" surfaces may be obtained.

Rotary-cut veneer is produced in large sheets by revolving a log against a knife, "slash-cut" veneer being run out in a continuous sheet in a manner similar to the unrolling of a roll of paper. The length of the sheet (parallel to the grain) is equal to the length of the knife, and the width of the sheets (across the grain) is limited only by the width which can be handled or by the presence of defects in the log. With most woods this method of cutting produces the finest figure for decorative work.

Many of the softer woods may be cut into veneer when green without preliminary treatment. Other woods must be steamed before they can be cut satisfactorily.

567. Plywood is the ultimate form in which veneer is used by the engineer in auto bodies, small boats, aircraft construction, and the like. Adjacent plies are generally placed with their grain at right angles.

As has been noted under the heading Timber, wood is naturally highly variable in its properties, particularly at different angles with its grain. In the manufacture of plywood it is possible to recombine the constituent layers so that the properties in different directions may be more nearly equalized. Two salient factors must always be considered in the construction of a satisfactory plywood: (1) it must always be composed of an odd number of layers; (2) layers symmetrically located with respect to the center one must have their grain respectively parallel and should be as nearly identical in all respects as possible. Failure to observe these precautions will result in a panel which will distort very seriously.

568. The woods most commonly utilized for plywood are: ash, oak, elm, birch, beech, maple, poplar, basswood, cottonwood, and mahogany. Many times all plies are of the same kind of wood. Sometimes different woods are combined in order to produce a plied material of special characteristics. Stiffness and strength against bending are largely a question of thickness combined with the modulus of elasticity of the material. Moreover, the central portion of a member under bending is very lightly stressed. In consequence of these facts it is possible to have a core of light and comparatively weak wood with surface plies of stronger material and thus produce a panel in which good strength and stiffness are combined with small weight. This procedure is most applicable in moderately thick plywood.

569. Properties and Characteristics of Plywood. In general, it is not possible to equalize all properties in all directions. Tensile strength is equalized in three-ply work when the core is 0.5 the total thickness. Bending strength and stiffness can be approximately equalized in three-ply work when the center ply is 0.7 the total thickness of the panel.

If all layers are of equal thickness this condition is reached only when the panel is composed of fifteen plies or more. Resistance to splitting cannot be equalized in three-ply construction; it is, however, equalized in the multiple-ply type.

Wood normally shrinks as much as 5 to 8 per cent across a board, in passing from green to oven-dry conditions. Plywood under similar treatment shrinks about 0.5 per cent, and that is practically equalized in both directions of a panel. This diminution of shrinkage is produced through the shear resistance of the glue layer. The thinner the individual plies the smaller will be these shrinkage stresses. It is obvious that very heavy plies might easily set up stresses of a magnitude sufficient to shear the glue or tear the adjacent wood fiber as the component parts tend to swell or shrink.

Since the number of combinations possible in plywood construction is very large, it is not possible to append any comprehensive table of strength. Table LVI, however, may serve as a guide to the possibilities of this type of construction.

570. Moisture Resistant Treatments. Plywood is only as good as the joint made by the glue between the plies. Specifications usually require that this joint shall not lose more than about 50 per cent of its original strength after soaking a three-ply specimen in cold water for 48 hours. Some of the more severe tests include strength requirements after 10 days' soaking in cold water, and after 8 hours in boiling water. Even the best glues known to the trade at present lose some of their strength when subjected to soaking or even to a very moist atmosphere for an extended period. This loss of strength can be somewhat diminished by a treatment

TABLE LVI

PROPERTIES OF PLYWOOD HAVING THREE PLIES OF EQUAL THICKNESS (PLIES $\frac{1}{30}$ TO $\frac{1}{16}$ INCH)

Kind of Wood	Tensile Strength, lb. per sq. in.		Modulus of Elasticity Perpendicular to Surface Grain
	Parallel to Surface Grain	Perpendicular to Surface Grain	
Birch, yellow	13,200	7,700	200,000
Ash, white	6,500	4,300	145,000
Basswood	6,300	4,100	85,000
Beech	13,000	7,300	165,000
Cottonwood	7,500	4,500	110,000
Elm, white	6,500	4,200	110,000
Maple [1]	9,000	6,000	150,000
Mahogany [1]	6,000	4,000	150,000
Oak, white	7,300	4,000	105,000
Poplar	7,400	4,500	115,000

[1] Values will vary with the species.

Modulus of elasticity parallel to the surface grain will closely approach that for the wood in the usual form. Numbers in the above table are given in round figures owing to the variations evident between tests on the same material.

of the exposed edges of the joint in heavy construction work. Most plywood is made from veneer so thin that the entire member must be covered with some water-resistant coating, and any treatment which will exclude moisture from the wood will tend to preserve the integrity of the glued joint.

The ordinary spar varnishes which are commonly held to be highly weather resistant are, nevertheless, only moderately effective as a means of excluding moisture from wood. Decidedly superior to these are the varnishes made with artificial resins. Some of the asphaltic and bituminous paints prove very satisfactory. The most highly water-resistant coating to date seems to be that which contains aluminum leaf. Such coatings are most effective when placed between coats of paint, varnish, enamel, or the like. Very many of the more common paints and varnishes are rendered more moisture resistant by the addition of leaf or powdered aluminum.

QUESTIONS

1. Name at least eight varieties each of hardwoods and of softwoods.

2. Identify the following terms relating to the growth and structural characteristics of timber: pith, bark, cell, vessel, medullary ray, cambium, and annual ring.

3. Distinguish between slash-cut and rift-cut lumber, and state the advantages of each.

4. Should boards for flooring be rift-cut or slash-cut?

5. Distinguish between spring wood and summer wood, and between sapwood and heartwood.

6. Describe the following defects of timber: encased knot, intergrown knot, spike knot, shake, check, pitch pocket, wane, cross-grain, warp, bow, cupping, and twist.

7. In what location on a simply supported beam under equal concentrated loads at the third points would a knot have a significant effect upon the strength of the beam?

8. Is shrinkage tangential to the annual rings greater or less than radial shrinkage? Explain why.

9. Discuss the importance of moisture in its effect on the properties of structural timber.

10. How is the moisture in green timber reduced in amount before the timber is used in construction work?

11. Discuss the effects of shrinkage on deterioration of timber.

12. What is the significance of the fiber-saturation point of wood?

13. What are the advantages of cutting timber in the winter?

14. Why are timber members ordinarily not used in tension?

15. Why is the determination of longitudinal shear important in designing structural timber beams?

16. Explain why stiffness of structural timber beams may be of importance.

17. How does the strength of timber under permanent load compare with its strength as determined by a short-time test?

18. What is meant by the term "basic stress"?

19. State typical values of maximum compressive and shearing strengths parallel to the grain for green and air-dry timber of the following varieties: hickory, red oak, white oak, Douglas fir, shortleaf pine, and white spruce.

20. Would you consider it desirable to use different unit stresses in designing small struts as compared with large structural beams of timber? Explain.

21. Compare the shock resistance of timber with that of steel, cast iron, and concrete.

22. What causes the decay of wood?

23. Name four antiseptics used for preserving timber, and describe the pressure process of injection.

24. Discuss the effect of preservative treatments on the strength of timber.

25. Describe the action of termites in destroying timber in buildings.

26. How would you protect a new timber building from the destructive action of termites? What corrective measures would you employ for a house infested with termites?

27. Describe the action of the teredo and limnoria in attacking timber piles.

28. What methods are employed to protect timber piles against attack by marine borers?

29. What are the advantages of plywood?

30. Describe the characteristics of three woodworking glues.

31. How is veneer cut?

32. Describe the physical properties of plywood.

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SECTION 7

BITUMINOUS MATERIALS

CHAPTER XXI

BITUMINOUS MATERIALS

BY LLOYD F. RADER

571. General. Bituminous materials are among the world's oldest and most useful materials of construction. They comprise both asphalts and tars. Asphalts from natural deposits were utilized by early civilizations as waterproofing materials and for preservation against the elements.

Wood tar was produced on a large scale in Norway and Sweden prior to 1661. A patent for the manufacture of coal tar was issued in England in 1681, and the substance was manufactured on a large scale in 1792. Sidewalks and bridge floors were constructed of asphalt-impregnated limestone in Europe about 1800 and in the United States about 1838. The first synthetic asphalt pavement was laid in Washington, D. C., in 1879, employing Trinidad Lake asphalt as the binder. Asphalt was first used for roofing in 1870.

Asphalt has attained widespread usage only within comparatively recent years, following the discovery that asphaltic residues can be obtained from certain crude petroleums when volatile components are removed by distillation. Distillation was first carried on in batch cylindrical stills. This method has been largely displaced by the continuous distillation process employing pipe stills and vacuum flash chambers. The transformation that takes place in distillation is purely physical. Asphalts may be further processed to change their properties for specific purposes.

Asphalts and tars are extensively used in the construction of roads and pavements, as roofing materials, for waterproofing and coating, and as bases for bituminous paint, varnish, enamel, and japan.

572. Definitions. **Bitumens* are defined as mixtures of hydrocarbons of natural or pyrogenous † origin or combinations of both frequently accompanied by their non-metallic derivatives, which may be gaseous, liquid, semisolid, or solid, and which are completely soluble in carbon disulfide. A *bituminous material* is composed essentially of bitumen. Other organic and inorganic matter may be present.

Many materials contain bitumen, but asphalt and tar are the two important bituminous materials in engineering construction. *Asphalt* is found in natural deposits and is produced artificially from petroleums; *tar* is produced only by artificial processes.

* *Asphalts* are defined as black to dark-brown solid or semisolid cementitious materials which gradually liquefy when heated, in which the predominating constituents are bitumens all of which occur in the solid or semisolid form in nature or are obtained by refining petroleum, or which are combinations of the bitumens mentioned with each other or with petroleum or derivatives thereof.

* *Tars* are defined as black to dark-brown bituminous condensates which yield substantial quantities of pitch when partially evaporated or fractionally distilled, and which are produced by destructive distillation of organic material, such as coal, oil, lignite, peat, and wood.

Bituminous mixtures are mixtures of asphalt or tar with mineral aggregates such as crushed stone, gravel, slag, sand, and dust.

ASPHALT

573. Types. There are two main types of asphalts: (1) *native asphalts* obtained from natural deposits, and (2) *petroleum asphalts* produced by refining petroleum oils which contain asphaltic material.

574. Trinidad Lake Asphalt. This native asphalt is obtained from Trinidad Lake on the island of Trinidad in the West Indies. The deposit is about 100 acres in extent and approximately 200 feet deep at its lowest point. The lake is fed from springs of maltha. The asphalt is excavated by hand, transported to the seacoast, loaded into the holds of vessels, and transported to refineries in the United States. The asphalt as found in the lake contains a great deal of fine mineral matter. The refining process consists of dehydration and sedimentation to remove water and to settle out some of the mineral matter. The refined Trinidad asphalt contains only about 56 per cent of bitumen, the remainder being largely fine mineral matter. Refined Trinidad asphalt is too hard for most paving uses; to reduce the consistency it is fluxed with an asphaltic oil, the resulting product being called asphalt cement.

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* Definitions adopted by the American Society for Testing Materials are marked with an asterisk.

† Produced by heat.

575. Bermudez Lake Asphalt. Bermudez asphalt is obtained from lake deposits in Venezuela. The deposits cover an area of about 900 acres but are only about 9 feet deep. The asphalt deposit contains débris and mineral matter. The methods of removal, transportation, and refining are similar to those for Trinidad asphalt. Refined Bermudez asphalt is composed of about 95 per cent bitumen, the remainder being fine mineral matter. It must be fluxed for use as a paving material.

576. Gilsonite. Gilsonite is a natural asphalt which occurs in vertical veins in Colorado and Utah. It is practically all bitumen and is hard and brittle. It is sometimes used to improve the properties of other asphalts. Asphalt cement containing gilsonite is tough and rubbery. Gilsonite is a valuable asphalt for manufacturing paints and varnishes.

577. Grahamite. Grahamite is a natural asphalt similar to gilsonite in properties. It is found in widely separated deposits. The material is variable in composition and physical properties since some deposits are composed of practically pure bitumen while others contain considerable mineral matter.

578. Petroleum Asphalt. Petroleum asphalt is obtained by fractional distillation of petroleum oil containing asphalt. It constitutes the major portion of the total production of asphalts.

With respect to asphalt content, petroleums may be classified as asphaltic, semi-asphaltic, and non-asphaltic petroleums. Solid paraffins may or may not be present in any of these classes but are usually present in the semi-asphaltic and non-asphaltic types. Asphalt is obtained as a residual product by fractional distillation of asphaltic and semi-asphaltic petroleums.

Asphaltic petroleum fields are located in California, Texas, Louisiana, Mexico, Venezuela, Colombia, Peru, Argentina, and Trinidad. Semi-asphaltic petroleum is found in the mid-continental field located in the states of Illinois, Kansas, Oklahoma, Texas, Arkansas, Louisiana, Colorado, Wyoming, Montana, Utah, and New Mexico. The petroleums from the fields in the eastern part of the United States are non-asphaltic.

Petroleum deposits usually occur in porous sandstones or limestones which are located between impervious layers of shale or rock. Deposits of petroleum are generally found at points where the bed of porous material is above its own general level. Petroleum is obtained by boring through the overlying strata until the oil-bearing rock is struck. Since gas, oil, and water accumulate at different levels in the porous rock by force of gravity, it is necessary to bore into the level at which the oil has collected. In some deposits the petroleum may be under such pressure that it is driven to the surface with great force when the oil rock is struck and a gusher results, but usually the oil must be pumped. Sometimes the capacity is increased by shooting the well with nitroglycerin to form a porous sump at the foot of the casing into which the oil seeps.

579. Constitution of Asphalt. Asphalt is a colloid. The essential constitution of asphalt is frequently given as asphaltenes, petroleum resins, and oily constituents. Asphaltenes are composed of carbon (or hydrocarbons) plus protective body in the form of polymerized resins. Petroleum resins are composed of a small amount of carbon (or hydrocarbons) with a great deal of protective body. The asphaltenes and the petroleum resins form the micelle or dispersed phase; the oily constituents form the dispersion medium.

TAR

580. Types. Tars of commercial importance may be classified as coal tar and water-gas tar.

581. Coal Tar. Coal tar is obtained by destructive distillation of bituminous coal. It is produced as a by-product in the manufacture of coke or illuminating gas. Coal tars may be further classified into coke-oven or gas-house tars, depending on whether coke or illuminating gas was the material produced.

Bituminous coal is charged into ovens or retorts where it is heated to high temperatures to drive off the volatile matter in the coal. The volatile constituents may be grouped into non-condensable and condensable products, the former including permanent gases and the latter aqueous liquor and tar. The volatile products pass by means of pipes to the hydraulic main which is a closed trough partly filled with water. A large proportion of the tar condenses in the hydraulic main and is removed. The vapors are then passed through a condenser which may be either air-cooled or water-cooled. More tar is condensed here and drawn off. The gases are passed through one or more "scrubbers" where the gases are washed with oils or chemicals to remove ammoniacal liquor from the tar. The rest of the tar is extracted by means of water sprays operated in connection with screens.

582. Water-gas Tar. Water-gas is manufactured from either anthracite coal or coke by introducing steam into the generator of the plant through a bed of the fuel which has been heated to an incandescent state. To make water-gas luminous it is enriched with a petroleum distillate which is usually gas-oil. The gas-oil is sprayed into a carbureter where it mixes with the water-gas and is vaporized. The mixture is passed through a superheater, a chamber partly filled with brick where the temperature is maintained at about 650° C. (1202° F.) so as to "crack" the oil vapors. Gases which burn with a luminous flame and tarry vapors are formed; these are passed through a washer, a scrubber, a condenser, and a tar extractor to remove the water-gas tar.

REFINING PROCESSES

583. General. The principal refining processes employed in manufacturing bituminous materials for industrial purposes are sedimentation, dehydration, distillation, oxidation, fluxing, and manufacture of cut-backs and emulsions.

584. Sedimentation. Native asphalts and crude petroleums contain some water and mineral and vegetable impurities. These impurities can to a large extent be removed by sedimentation, which is mechanical separation due to differences in specific gravity. Heating is necessary to remove impurities from native asphalts by sedimentation. Some of the water in crude tars may be removed by sedimentation.

585. Dehydration. It is usually necessary to remove water from petroleum and tar, particularly when water is held as an emulsion. A topping plant is ordinarily used for petroleum, in which the crude material is pumped under pressure through heated pipes and released in a vaporizer at atmospheric pressure. The water and oil vapors are condensed and separated by gravity; they do not again emulsify because of the absence of emulsifying agents and the low viscosity of the oil.

Tars are usually dehydrated by passing the crude material in thin films over heated baffle plates placed in an airtight chamber to which a vacuum is applied. The water and tar vapors are condensed and separated by gravity. It is difficult to remove all the water from tar.

586. Fractional Distillation. Fractional distillation is usually practiced to obtain asphalt from petroleum oil. This method is a process of mechanically separating volatile material from asphaltic residue.

Batch stills were formerly extensively employed in producing asphalt. The petroleum in the still is heated so that volatile products of low boiling points pass off as distillates, leaving asphalt as residue in the still. When steam is passed through the material in the still, the process is called steam distillation. The steam is mechanical in action and tends to reduce cracking.

The consistency of the asphaltic residue may vary from a hard asphalt of high consistency to a residual oil of low consistency, depending on the nature of the petroleum and the temperature and the length of time the heat is applied. The distillate is condensed and run into receivers; it may be further processed to yield gasoline, kerosene, naphtha, light fuel oil, and similar products.

The batch still has been largely displaced by the vacuum flash coil process. In this process the petroleum is run continuously through pipes which are heated so as to raise the oil to a temperature of about 385° C. (725° F.). The heated oil is then passed into the flash coil or chamber which is under a partial vacuum. Distillation under reduced pressure lowers the boiling points of the hydrocarbons so that many hydrocarbons pass over as distillate without breaking up chemically. The distillate is quickly separated from the residual material and passes up and out of the flash chamber at a temperature of about 355° C. (671° F.). The distillate is condensed and run into tanks. The residual asphalt is run out of the bottom of the flash chamber into receivers. Asphalts refined entirely by fractional distillation are called straight-reduced asphalts. The distillation process may be controlled so as to produce asphaltic residues of varying consistencies; these may be classified as fluid residual oils, asphalt cements, and refined asphalts.

587. Cracking. Petroleum oils may be subjected to a process known as "cracking" in which changes in the constitution of the hydrocarbons occur. Cracking is most effectively produced by distilling under pressure but may occur if the material in a still not under pressure is heated without mechanical or steam agitation. Refiners frequently resort to cracking to increase the yield of the lighter distillates so as to obtain more gasoline from the crude oil. Asphalts manufactured by the cracking process are not considered to have good properties. "Cracked" asphalts are likely to be heterogeneous in character and may be highly susceptible to temperature changes.

588. Oxidation. The process of oxidation consists of blowing air through molten asphalt or petroleum residuum, causing a chemical reaction. The usual apparatus for this is a cylindrical shell still of the batch type, mounted either horizontally or vertically. Air is forced through perforated pipes located in the bottom of the still under a pressure sufficient to overcome the static head of the material in the still and to cause intimate contact and agitation. From 20 to 30 cubic feet of air per ton of asphalt processed is required. Temperature is maintained from 205° C. (401° F.) to 260° C. (500° F.); the reaction is exothermic, requiring little external heat after it has started. The charging stock is semisolid asphalt or liquid petroleum residual product which has been distilled to remove volatile fractions and bring the flash point above 205° C. (401° F.).

The oxygen of the air combines with part of the hydrogen in the hydrocarbon molecules forming water which is removed as steam, and the hydrocarbon molecules form larger, denser compounds of higher molecular weight (called polymerization). The amount of added oxygen is small. Oxidation causes important changes in the characteristics of asphalt, the continued application of air yielding asphalts of progressively decreasing penetrations, higher softening points, and lower ductilities. The oxidation process has not been applied to tars.

589. Fluxing. Fluxing is the process of combining bituminous materials of low viscosity to those of high viscosity in order to soften the latter. The operation is usually carried on in large tanks or kettles in which the heavy product is melted and the required amount of flux oil is added. The materials are mixed together by agitation with steam or mechanical agitators. Refined asphalts which have been fluxed so that their consistency is suitable for paving use are termed asphalt cements.

590. Manufacture of Cut-back Bituminous Materials. Both asphalt and tar cut-back products are manufactured. Cut-back asphalts are produced by combining petroleum distillates with asphalt cement.* They differ from ordinary fluxed asphalt, which is an asphalt blended with a liquid residual oil. Tar cut-backs are similarly prepared by adding distillate products to tar.

The function of the distillate in bituminous cut-backs is to liquefy the bituminous cement so as to facilitate its application and manipulation in industrial use, particularly in the construction of road surfaces. The distillate serves as a substitute for heat which is used to liquefy bituminous cements prior to application. Distillate has an advantage over heat for some classes of work since its liquefying effect can be made to extend over a longer period of time.

TESTING OF BITUMINOUS MATERIALS

591. General. The properties of bituminous materials are determined by tests. Detailed descriptions of methods of testing bituminous materials may be found in the Standard Methods of Tests of the American Society for Testing Materials and the American Association of State Highway Officials.

592. Specific Gravity. Specific gravity of liquid bituminous materials may be determined by means of a hydrometer; of semisolid materials by a pycnometer; and of solid materials by weighing in air and in water. Tests are usually made on the materials at a temperature of 25° C. (77° F.). The determination of specific gravity of bituminous materials is of value in identifying materials, in checking uniformity of different shipments, and as one of the factors in determining percentage of voids in compressed bituminous paving mixtures.

593. Consistency. Consistency refers to the viscosity of bituminous materials; it is of importance in determining the suitability of bituminous materials for various purposes.

Ideally the consistency should be determined in terms of *absolute viscosity*. This is difficult, however, owing to the wide range in viscosity of various bituminous products. The absolute viscosity at 35° C. (95° F.) of tars varying in consistency from light to extra heavy has been deter-

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* Prevost Hubbard: Cut-back Asphalts, Their Characteristics and Use, *Proc. Tenth Annual Asphalt Paving Conference*, December, 1932.

mined by means of the Koppers viscosimeter.* (See Table LXI.) With this instrument, viscosity is determined by timing the flow of the material through a capillary tube. The lower end of the tube is immersed in the sample, and the upper end is connected with a partly evacuated reservoir. The time is noted for the sample to pass between two points on the capillary tube. The absolute viscosity in poises can be calculated from this time, the vacuum applied, the distance between the fixed points, and the radius of the bore of the capillary tube. The unit "poise" may be defined as follows: If the space between two planes, 1 centimeter apart and each 1 centimeter square, is filled with a fluid and a tangential force of 1 dyne is required to move one of the planes 1 centimeter in 1 second, the fluid has a viscosity of 1 poise.

The common methods of determining consistency in industrial use comprise the penetration test, the Engler and Saybolt Furol viscosimeter tests, and the float test. The *penetration test* determines the consistency of semisolid asphalts by measuring the depth of penetration of a standard needle into the surface of the material in units of tenths of millimeters under standard conditions of load, time of application, and temperature. *Normal penetration* is the penetration determined under a load of 100 grams for a time of 5 seconds at a temperature of 25° C. (77° F.). The penetration test is used to determine the consistency of asphalt cements for use in sheet asphalt, asphaltic concrete, asphaltic macadam, fillers for block pavements, and residues from heating tests. The penetration test is not well adapted to testing semisolid tars because of their high surface tension.

Viscosity of liquid bituminous materials is ordinarily determined by either the Engler or the Saybolt Furol viscosimeter. *Specific viscosity* is determined by means of the Engler instrument by dividing the time for 50 cubic centimeters of bituminous material to flow through the orifice at a specified temperature by the time for the same amount of water to flow through the orifice under the same head at a temperature of 25° C. (77° F.). With the Saybolt Furol viscosimeter, the viscosity is expressed as the number of seconds for 60 cubic centimeters of the bituminous material to flow through the standard Furol orifice at a specified temperature.

The float test is suitable for materials which are too viscous for the viscosimeter test and too soft for the penetration test. The procedure consists of molding a small plug of the bituminous material in a brass collar which is screwed into an aluminum saucer or float. After cooling at 5° C. (41° F.), the float is placed on a water bath at a specified temperature and the time measured for the plug to become sufficiently fluid to permit water to break through into the saucer.

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* E. O. Rhodes, E. W. Volkmann, and C. T. Barker: New Viscosimeter for Bitumens Has Extended Range, *Engineering News-Record,* v. 115, No. 21, November 21, 1935, pp. 714-718.

594. Softening Point. Softening point is the temperature at which a bituminous material softens under arbitrary conditions of test. Since bituminous materials are mixtures of many different hydrocarbon compounds of varying properties, there is no critical temperature at which a change from a solid to a liquid state occurs; therefore any method of determining softening point is entirely arbitrary and dependent upon the method of test. Two methods of test are in common use: the ring and ball test for both asphalts and tars and the cube-in-water test for tars only.

The determination of softening point is of value in identifying materials and their methods of manufacture, as for example in identifying oxidized asphalt which has a high softening point compared with asphalt of the same normal penetration produced entirely by distillation. The determination of softening point is also of value in connection with the selection of asphalt and tar products for use as seal coats, fillers, and binders since high-softening-point materials are generally less susceptible to temperature changes than those of low softening point and are less likely to bleed in hot weather.

595. Ductility. The ductility test is conducted by stretching a briquet of asphalt with a minimum cross-sectional area of 1 square centimeter at the rate of 5 centimeters per minute at the temperature of 25° C. (77° F.) in a water bath until it breaks. In a normal test the asphalt stretches into a thin thread before separating.

The ductility test is used in identification and in controlling the manufacture of asphalts. Most petroleum asphalts produced entirely by distillation have a ductility over 100 centimeters at 25° C. (77° F.). Ductility of asphalts as measured at 25° C. (77° F.) is decreased by the oxidation process. The test is used to determine the degree of oxidation.

596. Flash Point. The flash point of a bituminous material is the temperature at which, when the material is heated at a specified rate, sufficient vapors are given off to cause a flash over its surface when a small flame is brought in contact with them. It is used in identification of various types of bituminous materials. Cut-back products have lower flash points than residual materials on account of the presence of distillates. The flash point is considered to be a critical temperature below which bituminous materials may be manipulated without danger of fire.

597. Volatilization Test. This test is applied to asphalts to determine the loss which occurs by volatilization when a 50-gram sample is maintained in an oven at a temperature of 163° C. (325° F.) for a period of 5 hours. The loss by volatilization is expressed as a percentage of the original material. The consistency of the residue from the volatilization test may be determined by the penetration or float tests and compared with the consistency of the original materials. Thus the amount an asphalt is likely to volatilize and harden at an elevated temperature can be determined. An asphalt cement should be required to show a low loss by volatilization and a small amount of hardening due to such loss.

598. Distillation Test. The distillation test is conducted on tars and cut-back asphalts by heating a sample of known weight of the bituminous material at a specified rate to various temperatures and collecting and measuring the distillates given off up to each temperature. The test is useful in determining the constituents of tars and in determining the amount and character of residue from asphalt and tar cut-backs which they may be expected to develop by volatilization of distillates when placed in service. Also the relative rapidity with which such residue will be developed after application may be determined by obtaining the amounts of light and heavy distillates in the cut-back materials.

599. Solubility Test. The percentage of bitumen in a bituminous material may be determined by its solubility in carbon disulfide. Bitumen is the part of bituminous materials which has cementing properties. It is customary to purchase bituminous materials on the basis of bitumen content. Petroleum asphalt is practically pure bitumen. Most native asphalts contain organic and inorganic matter insoluble in carbon disulfide in considerable quantity. Practically all the insoluble matter in tar is organic and consists of free carbon in the form of small particles uniformly distributed. Tars with bitumen contents above 95 per cent are called low-carbon tars; those with bitumen contents less than 95 per cent are known as high-carbon tars. Gas-house coal tars may usually be distinguished from coke-oven coal tars by their relatively high content of free carbon. Refined water-gas tars have a small percentage of free carbon.

Carbenes comprise the bitumen in petroleum and asphalt products which is insoluble in carbon tetrachloride. The percentage of bitumen insoluble in carbon tetrachloride is reported upon the basis of total bitumen taken as 100 per cent. The difference between the material insoluble in carbon disulfide and in carbon tetrachloride is the bitumen insoluble in the latter. The presence of carbenes indicates incipient cracking due to overheating in production. Where carbenes in petroleum residuums are accompanied by an appreciable amount of organic matter insoluble in carbon disulfide, indications point strongly to injury of the material by decomposition of some of the hydrocarbons present. The test is not applicable to tars.

Asphaltenes comprise bitumen in petroleum and asphalt products which is insoluble in paraffin naphtha of 86 degree Baumé gravity. Asphaltenes give body and consistency as well as cementitiousness to bituminous materials. The test is useful in identifying asphalts, particularly when considered in connection with other tests. Native asphalts are highly soluble in paraffin naphtha. Straight-reduced petroleum asphalts have a relatively low asphaltene content, but oxidation increases the percentage of asphaltenes. The test is not used for tars.

600. Oliensis Spot Test. G. L. Oliensis[*] has proposed a test for determining qualitatively the degree of physical heterogeneity in asphalt. The test depends upon the precipitation that takes place when asphalt is dissolved or dispersed by 5.1 times its volume of petroleum naphtha. "Carbenoids" is the name of the precipitated bodies.

The specifications for the naphtha solvent require that it shall be a straight-run overhead distillate free from cracked products of any kind, and shall conform to the following requirements:

Gravity, degrees American Petroleum Institute 49 to 50.

Distillation:

Initial boiling point	Above 150° C. (300° F.)
50 per cent over	170 to 180° C. (335 to 355° F.)
End point	Below 210° C. (410° F.)
Aniline number (A.S.T.M. Designation—D91—33)	60 to 65° C. (138 to 145° F.)

When a drop of the asphalt solvent mixture is placed on a filter paper, it produces either a uniform brown circular stain or a brown stain with a much darker spot in the center. Asphalts which produce a uniform spot by this test are classified as homogeneous or negative, while those producing a darker spot as heterogeneous or positive.

The theory of this test is explained by Oliensis as follows. The introduction of a solvent will decrease the solvent power of the external phase of the colloidal system and will tend to precipitate the dispersed phase. The greater the quantity of solvent added, the greater is the amount of flocculation caused and the wider the range of hydrocarbons in the asphalt affected. On the other hand, the amount of solvent may be reduced until a point is reached where no flocculation at all results, as is illustrated in cut-back asphalts where the volume of naphtha is seldom as much as twice that of the asphalt. If, however, the amount of the naphtha is kept at some intermediate point relatively near to that at which flocculation may be expected to begin, a wide divergence appears in different asphalts in respect to their tendency to flocculate.

Oliensis has stated that this test will identify as heterogeneous all petroleum asphalts that have been subjected to temperatures higher than are normal in the regular steam-refining processes. Hence it will detect (*a*) cracked asphalts, (*b*) steam-refined or vacuum-process residuals that have been accidentally subjected to higher temperatures than are normal, and (*c*) the more highly blown asphalts that have been subjected to high temperatures for prolonged periods of time. The following factors may also cause an asphalt to be classified as heterogeneous even though high

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[*] *Proc. Am. Soc. Test. Mats.*, v. 33. 36, and 37, Part II, 1933, 1936, and 1937.

temperatures or cracking were not involved: waxy bodies, acid sludge bodies, the combination of incompatible fractions in so-called "synthetic" asphalts, and exposure to air.

With asphalts containing fine non-bituminous matter, a dull, central streak is always obtained. Since the carbenoids of a heterogeneous asphalt are soluble in or dispersed by xylene, this solvent offers a means of distinguishing between carbenoids and such fine non-bituminous matter. If the streak is obtained with xylene as well as with naphtha, the original streak was caused by the presence of non-bituminous matter; but if the streak does not appear using xylene, carbenoids are present in the asphalt.

PROPERTIES OF BITUMINOUS MATERIALS

601. Asphalt Cements. The properties of straight-reduced and air-blown asphalt cements prepared from the same residuum are compared in Table LVII. Although these asphalt cements are of practically the same normal penetration, the air-blown asphalt is much less susceptible to temperature changes, as shown by the penetration values at 32° F. and 115° F.

TABLE LVII

Analyses of Steam-distilled and Air-blown Asphalts Manufactured from the Same Mexican Residuum [1]

Test	Mexican Residuum Used	Steam-distilled	Air-blown
Specific gravity, 77° F.	0.996	1.047	1.017
Flash point (Cleveland open cup), ° F.	410	570	460
Softening point (ring and ball), ° F.	....	128	157
Penetration at:			
77° F. (100 g., 5 sec.)	....	55	56
32° F. (200 g., 60 sec.)	....	18	31
115° F. (50 g., 5 sec.)	....	260	123
Ductility at:			
77° F. (5 cm. per min.), in cm.	....	100+	4.0
39.2° F. (5 cm. per min.), in cm.	....	5.0	....
Solubility in CS_2, per cent	99.9	99.9	99.9
Solubility in CCl_4, per cent	99.9	99.8	99.8
Spot test (Oliensis)	Neg.	Neg.	Pos.
Yield, in per cent by weight	....	65	96

[1] Gene Abson: The Manufacture of Asphalt, *Civil Engineering*, February, 1938.

The oxidation of asphalt by air blowing causes an increase in the amount of asphaltenes; this corresponds to an increase in softening point. Oxidation decreases the resin content; this corresponds to a low ductility.

Analyses of typical asphalt cements for paving mixtures produced by distillation from crude oils obtained from different sources are presented

TABLE LVIII

Analyses of Typical Asphalt Cements Used in Paving Mixtures[1]

Test	Mexican; Steam, Continuous (no oxidation)	Mid-continent; Pipe Still and Vacuum Chamber (some oxidation)	California; Batch, Steam (no oxidation)
Specific gravity, 77° F.	1.040	1.012	1.020
Flash point (Cleveland open cup), ° F.	530	600	565
Softening point (ring and ball), ° F.	135	130	124
Penetration at:			
77° F. (100 g., 5 sec.)	50	45	54
32° F. (200 g., 60 sec.)	16	14	11
115° F. (50 g., 5 sec.)	225	212	350+
Ductility at:			
77° F. (5 cm. per min.), in cm.	150+	150+	150+
Solubility in CS_2, per cent	99.9	99.9	99.9
Solubility in CCl_4, per cent	99.9	99.8	99.9
Solubility in 86° Bé naphtha, per cent	71.2	77.8	89.8
Volatilization loss, (50 g., 5 hr., 325° F.) per cent	0.02	0.04	0.02
Penetration after loss	45	44	52
Loss in penetration, per cent	10.0	2.2	4.0
Spot test (Oliensis)	Neg.	Neg.	Neg.

[1] Gene Abson: The Manufacture of Asphalt, *Civil Engineering*, February, 1938.

TABLE LIX

Summary of Asphalt Institute Specifications for Cut-back Asphalts

Specification designation.	RC–1	RC–2	RC–3	RC–4	MC–1	MC–2	MC–3	MC–4	MC–5
General requirement	The material shall be free from water and shall meet the following requirements:								
Flash point (open tag), ° F.	80+	80+	80+	80+	.....	150+	150+	150+	150+
Furol viscosity, at 77° F.	.....	.....	.....	.....	40–150	.....	.....	.....	.....
at 122° F.	80–160	200–400	.....	.....	.....	.....	.....	.....	.....
at 140° F.	.....	.....	275–400	700–1400	.....	150–250	300–500	500–800	.....
at 180° F.	.....	.....	.....	.....	.....	.....	.....	.....	170–230
Distillation, per cent by volume: Total distillate, to 374° F.	5+	.....	.....	.....	.....	.....	.....	.....	.....
to 437° F.	12+	10+	3+	0.5+	10–	2–	2–	1–	1–
to 600° F.	25+	20+	14+	7+	25+	10–20	8–20	16–	14–
to 680° F.	40–	35–	30–	25–	50–	27–	25–	25–	20–
Tests on residue from distillation: Penetration at 77° F., 100 g., 5 sec.	60–120	60–120	60–120	60–120	70–300	100–300	100–300	100–300	100–300
Ductility at 77° F.	60+	60+	60+	60+	60+	60+	60+	60+	60+
Per cent soluble in carbon disulfide	99.5+	99.5+	99.5+	99.5+	99.5+	99.5+	99.5+	99.5+	99.5+

in Table LVIII. The California asphalt has a high susceptibility to temperature changes, as shown by the penetration values, and a lower asphaltene content, as shown by the solubility in naphtha, than the Mexican and Mid-continent asphalts.

602. Liquid Asphaltic Materials. In Table LIX, specifications of the Asphalt Institute are given for cut-back asphalts of the rapid-curing and medium-curing types. Numerical values opposite the individual tests, if followed by a + sign, signify not less than the value shown, and if followed by a − sign, not more than the value shown. Table LX gives specifications of the Asphalt Institute for slow-curing liquid asphalts.

TABLE LX

SUMMARY OF ASPHALT INSTITUTE SPECIFICATIONS FOR SLOW-CURING LIQUID ASPHALTS

Specification designation	SC-1	SC-2	SC-3	SC-4
General requirement	The material shall meet the following requirements:			
Water and sediment, per cent	2−	2−	2−	2−
Flash point (Cleveland open cup), ° F.	150+	200+	200+	250+
Furol viscosity, at 77° F.	20–150	......	......	......
at 122° F.	......	200–320	......	......
at 140° F.	......	......	150–300	350–550
Distillation, per cent by volume: Total distillate, to 437° F.	......	2−	2−	2−
to 600° F.	.....	15−	10−	8−
to 680° F.	50−	25−	20−	18−
Tests on residue from distillation: Float test, 122° F.	50−	25+	25+	25+
Per cent soluble in carbon disulfide	99.0+	99.0+	99.0+	99.0+

The flash-point requirements are set to insure materials that may be safely manipulated. The viscosity is specified for the various grades of material to insure proper consistency for application of the liquid asphalt to aggregates. The requirements of the distillation test are for the purpose of controlling the rate of curing, and the consistency specifications on the residue from the distillation test are for the purpose of insuring a proper grade of asphalt as a binding agent for the aggregates after curing has taken place.

TABLE LXI

Summary of A.S.T.M. Specifications for Tars

Specification designation	T-1	T-2	T-3	T-4	T-5	T-6	T-7	T-8	T-9	T-10	T-11	T-12
Water by volume, max., per cent	2.00	2.00	2.00	2.00	1.5	1.5	1.0	none	none	none	none	none
Specific gravity at 25°/25° C., min.	1.08	1.08	1.09	1.09	1.10	1.10	1.12	1.14	1.14	1.15	1.16	1.16
Specific viscosity, Engler, 50 cc. at 40° C.	5–8	8–13	13–22	22–35	.....	.....	.....	.....	.....	.....	.....	.....
Specific viscosity, Engler, 50 cc. at 50° C.	.....	.....	.....	.....	17–26	26–40	.....	.....	.....	.....	.....	.....
Float test at 32° C., sec.	.....	.....	.....	.....	.....	.....	50–80	80–120	120–200	.....	.....	.....
Float test at 50° C., sec.	.....	.....	.....	.....	.....	.....	.....	.....	.....	75–100	100–150	150–220
Absolute viscosity, in poises at 35° C. (95° F.)[1]	0.70–1.20	1.20–2.05	2.05–3.51	3.51–6.01	6.01–10.3	10.3–23.0	23.0–67.4	67.4–197	197–578	578–1690	1690–4960	4960–19,000
Distillation test on water-free material:												
Total distillate by weight, up to 170° C., max., per cent	7.0	7.0	7.0	5.0	5.0	5.0	3.0	1.0	1.0	1.0	1.0	1.0
Total distillate by weight, up to 270° C., max., per cent	35.0	35.0	30.0	30.0	25.0	25.0	20.0	15.0	15.0	10.0	10.0	10.0
Total distillate by weight, up to 300° C., max., per cent	45.0	45.0	40.0	40.0	35.0	35.0	30.0	25.0	25.0	20.0	20.0	20.0
Softening point (ring-and-ball method) of residue from distillation test	60° C. max.	65° C. max.[2] 35–65° C.[3]	35 to 65° C.	35 to 65° C.	35 to 70° C.	35 to 70° C.	35 to 70° C.	35 to 70° C.	35 to 70° C.	40 to 70° C.	40 to 70° C.	40 to 70° C.
Total bitumen (soluble in carbon disulfide) by weight, min., per cent	88	88	88	88	83	83	78.0	78.0	78.0	75.0	75.0	75.0
Typical uses	Prime coat		Prime coat and light surface treatment		Surface treatment and road mix		Surface treatment, road mix, plant mix, and seal coat			Surface treatment, plant mix, seal coat, penetration, and crack filler		

[1] Data published by Koppers Products Co. Not an A.S.T.M. specification.

[2] When used as a primer.

[3] When used for surface treatment.

603. Tars. A summary of the American Society for Testing Materials specifications for tars of twelve different grades is given in Table LXI. It will be noted that the consistency requirements have been set so that there are no gaps or overlappings in the absolute viscosity requirements for the different grades of tars. Since testing laboratories are ordinarily equipped with the Engler viscosimeter and the float test, consistency is specified in terms of these tests.

Specifications for cut-back tars are given in Table LXII.

TABLE LXII

SUMMARY OF A.S.T.M. SPECIFICATIONS FOR CUT-BACK TARS

Specification designation	T.C.B.-5	T.C.B.-6
Water by volume, maximum, per cent	1.0	1.0
Specific gravity, 25°/25° C., minimum	1.09	1.09
Specific viscosity, Engler, 50 cc. at 50° C.	17-26	26-40
Distillation test on water-free material:		
Total distillate by weight, up to 170° C.	2.0-8.0	2.0-8.0
Total distillate by weight, up to 200° C.	5.0 min.	5.0 min.
Total distillate by weight, up to 235° C.	8.0-18.0	8.0-18.0
Total distillate by weight, up to 300° C.	25.0 max.	35.0 max.
Softening point (ring-and-ball method) of residue from distillation test	40-70° C.	40-70° C.
Total bitumen (soluble in carbon disulfide) by weight, minimum, per cent	80.0	80.0
Typical uses	Surface treatment. Road mix and plant mix when low-temperature application and quick-setting are desired	

ASPHALT PAVING MIXTURES

604. General. The use of asphalt cement in paving mixtures comprises one of the most important applications of asphalt. Asphalt paving mixtures may be of the sheet asphalt or asphaltic concrete types; these mixtures are extensively used for paving city streets.

Sheet asphalt is usually composed of 9 to 12.5 per cent of asphalt cement, 10 to 20 per cent of mineral filler such as limestone dust, and the remainder of well-graded sand passing a No. 10 sieve. *Asphaltic concrete* is composed of asphalt cement, mineral filler, sand, and crushed stone. The stone may be coarse graded or fine graded aggregate. The composition is dependent upon the gradation of the stone. *Binder course* is an asphaltic concrete mixture composed of coarse graded aggregate with no filler and is used as a course on top of the Portland cement concrete base and under the sheet asphalt surface course to give increased stability to the latter.

605. Design of Asphalt Paving Mixtures. Asphalt paving mixtures should be designed to have stability which is resistance to displacement by traffic, and to be resistant to cracking, particularly at low temperatures, and to be watertight.

In the stability test as developed by Hubbard and Field a compressed cylindrical briquet of the paving mixture, or core specimen taken from the pavement, is heated to 60° C. (140° F.) and placed in a close-fitting cylindrical mold with a circular bottom orifice of standard diameter. A 2-inch mold is ordinarily used for sheet asphalt and similar fine aggregate mixtures, while a 6-inch mold is used exclusively for coarse mixtures. The orifice for 6-inch specimens produces approximately the same stability values for sheet asphalt mixtures as the 2-inch mold. The maximum load developed in forcing the mixture through this orifice is recorded in pounds as a measure of the stability of the mixture. The test is made at 60° C. (140° F.) as this represents the maximum temperature which the mixture is likely to reach under service conditions.

The stability test is of value in determining the resistance to displacement under traffic of asphalt paving mixtures prepared for use and of asphalt pavements as laid. It is also of value in developing the most suitable formula or percentage combination of constituents to adopt for paving plant operation. A minimum stability of 2000 pounds has been found sufficient to resist displacement under heavy concentrated traffic. Above this value, excessively high stability may, however, be conducive to cracking of the mixture under service stresses.

The flexure test on a compressed beam of paving mixture, or a beam specimen taken from the pavement, at a low temperature has been developed by Rader * to determine resistance to cracking. Modulus of rupture and modulus of elasticity in flexure are determined. Modulus of rupture is a measure of the tensile strength of the mixture. Modulus of elasticity is a measure of the stiffness of the material. The greater the modulus of elasticity, the greater the stress set up in the material for a given change of length. From the standpoint of designing a mixture to resist cracking, it is desirable to have a high modulus of rupture and a low modulus of elasticity.

From the standpoint of producing watertight mixtures, the voids in the mineral aggregate should be filled with asphalt cement so that the voids in the compressed mixture will vary from about 1 to 5 per cent.

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* L. F. Rader: Investigations of the Physical Properties of Asphaltic Mixtures at Low Temperatures, *Proc. Am. Soc. Test Mats.*, v. 35, Part II, 1935.

The voids in the mineral aggregate should not be overfilled with asphalt since this practice reduces stability and does not allow for expansion caused by temperature changes.*

606. Plant Mixing. Plants for mixing large quantities of asphalt paving mixtures of high type consist essentially of (1) asphalt storage and heating tanks, (2) an aggregate heater known as a dryer, (3) screens and bins for separating and storing the various sizes of heated aggregate, (4) weighing devices for proportioning the mixture, and (5) a mechanical mixer (Fig. 137). The mixer is usually of the pug type which consists of a steel box equipped with two horizontal shafts on which are mounted blades set so as to throw the material toward the center of the mixer, but may be of the rotary type which consists of a cylindrical steel drum provided with shelves and with a tight-fitting cover so that the mixture can be kept under an air pressure of about 50 pounds per square inch.

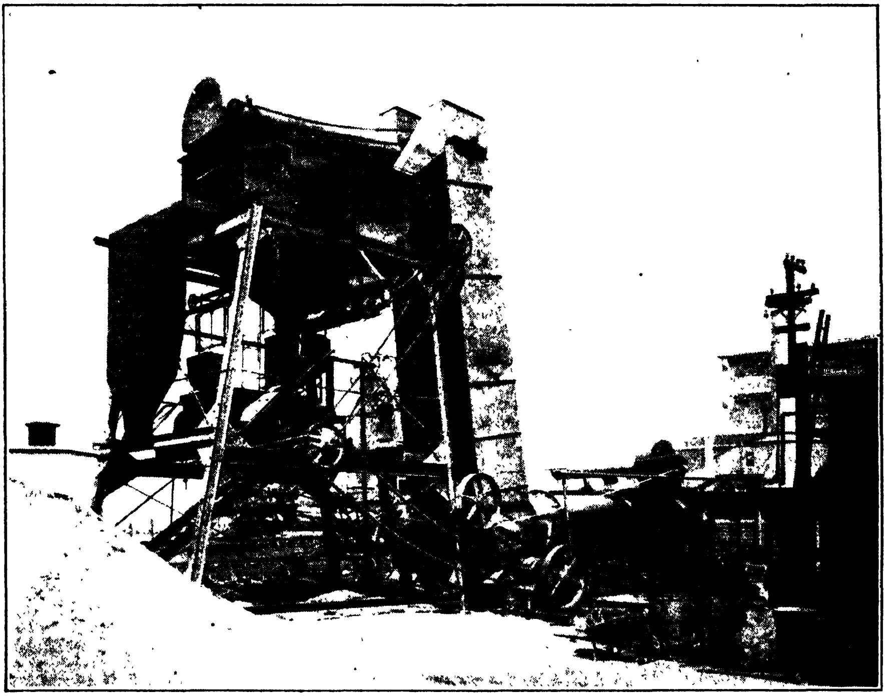

FIG. 137.—Asphalt Paving Plant. (Courtesy of Barber Co.)

The control of temperature is a necessary feature of paving-plant operation. Pyrometers and thermometers with recording gauges are in-

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* W. J. Emmons: Stability Experiments on Asphaltic Paving Mixtures, *Public Roads*, January, 1934.

stalled in well-designed plants in the asphalt tanks, dryer, bins, and mixer. Temperatures between 121° C. (250° F.) and 177° C. (350° F.) should be obtained depending on the type of mixture. Overheating of asphalt paving mixtures is detrimental since the penetration of the asphalt is decreased, indicating that hardening takes place, the softening point of the asphalt is increased, and the ductility is decreased. This action is similar in effect to oxidation. Such overheating may reduce the resistance of paving mixtures to cracking and may shorten the life of a pavement. Very high temperatures may cause charring of the asphalt, destroying its cementing ability.

The aggregates should be thoroughly mixed in the mixer for at least 15 seconds prior to the introduction of the hot asphalt cement. Mixing of the asphalt and aggregates should be sufficient to secure a homogeneous mixture of aggregate particles uniformly coated with asphalt, but such mixing should not be unduly prolonged since the thin films of hot asphalt in contact with air are readily hardened in a manner similar to oxidation. From 15 to 30 seconds for wet mixing is usually required.

607. Placing Mixtures on the Street. Asphalt paving mixtures should be covered with canvas to retain the heat during transportation from the plant to paving project. Paving mixtures are usually shoveled into place and spread by hand, but finishing machines are sometimes employed. Each load should be dumped just outside of the area on which it is to be spread, preferably upon a steel dump board. This procedure is necessary to secure uniform density of the pavement. The mixture is distributed

FIG. 138.—Placing Asphaltic Concrete Paving Mixture on Street. (Courtesy of B. E. Gray.)

into place by means of hot shovels and spread with hot rakes in a loose layer of uniform density and correct depth (Fig. 138).

The mixture is then compacted by rolling with rollers of 8 to 10 tons weight. Three-wheel rollers are preferable for initial rolling; tandem rollers are suitable for final rolling. A three-wheel roller equipped with an auxiliary fourth roller operated by hydraulic pressure is sometimes used to smooth the surface of the pavement. Rolling to secure a pavement of high density is extremely important to secure durability.*

608. Rock Asphalt. Rock asphalt consists of sandstone or limestone naturally impregnated with asphalt. The sandstone type is mined principally in Kentucky, and the limestone type in Texas and Alabama. The rock is usually in consolidated form in nature and must be crushed. The asphalt content and grading of the aggregate vary in some deposits so that rock asphalts of different compositions must be combined to produce a material suitable for construction purposes.

It is shipped in cars to the site of construction, where it may be shoveled from the cars, distributed, and rolled to final form without application of heat. It is used primarily for road construction, sidewalks, and tennis courts. Kentucky rock asphalt contains a high penetration asphalt; its stability under load depends largely upon the aggregate.

609. Cold-lay Asphalt Paving Mixtures. A common type of cold-lay asphalt paving mixture is composed of a hard pulverized asphalt, a flux oil, and aggregate consisting of mineral filler, sand, and sometimes crushed stone. Such a mixture will remain in a loose condition for a long period of time if uncompressed, but when it is subjected to pressure, the flux oil comes into intimate contact with the particles of powdered hard asphalt producing an asphalt cement which binds the aggregate particles into a consolidated mass. Such mixtures can be prepared in advance of construction and stored until needed. Cold-lay mixtures require less equipment than the hot type of mixtures.

EMULSIONS

610. Definition of Emulsion. An emulsion is a system containing two liquid phases, one of which is dispersed as globules in the other. The two liquids must be immiscible or at least partially immiscible. The liquid in the form of globules is called the dispersed phase; the liquid surrounding the globules, the continuous phase.

611. Stabilization. Owing to the work required for dispersion, the surface energy of the interface formed between the two liquids will be

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* L. F. Rader: Correlation of Low Temperature Tests with Resistance to Cracking of Sheet Asphalt Pavements, *Proceedings Association of Asphalt Paving Technologists*, January, 1936.

great and consequently the tendency for aggregation of dispersed globules will be great, the merest contact of the globules resulting in aggregation. In order to secure a desired degree of permanence, a small amount of an emulsifying agent to aid in emulsification and to stabilize the emulsion is added. The emulsifying agent usually forms a third phase which separates the two liquid phases by forming a protective film about the dispersed phase and thus preventing coalescence of the droplets of the dispersed phase. For bituminous emulsions stabilization is usually attained by adding a suitable viscous substance such as soap, sulfonated oil, or protein. Clays, oxides, hydrosilicates, and acids are also used.

612. Types of Emulsions. With any two liquids, such as oil and water, two types of emulsion are possible. When water is the continuous phase, the emulsion is called the oil-in-water type. When oil is the continuous phase and water is dispersed throughout the oil, the emulsion is called the water-in-oil type. Bituminous emulsions common in industry are ordinarily of the oil-in-water type.

If the emulsifying agent is more readily wetted by water than by oil, the oil-in-water type results, but if the emulsifying agent is more readily wetted by oil than by water, the water-in-oil type results. For example, sodium oleate is soluble in water, lowers the surface tension of water more than oil, and is more readily wetted by water; when used as an emulsifying agent, it produces an oil-in-water type of emulsion. On the other hand, calcium oleate, which is soluble in oil and is wetted more by oil than water, ordinarily produces a water-in-oil emulsion.

613. Manufacture of Emulsions. Manufacture of bituminous emulsions involves breaking up the bituminous material into minute globules and mixing it with water and one or more emulsifying agents by vigorous mechanical agitation while the phases are both freely liquid. This may be accomplished by two types of machines: agitators and colloid mills. Agitators such as paddle mixers and centrifugal pumps have been largely displaced by colloid mills. These mills, consisting of rotating disks operating at very high peripheral velocity, develop a shearing effect in the liquids and produce rapid dispersion. While the principles of emulsion manufacture are simple, the quality of the product is affected by factors such as temperature, concentration of phases, bituminous material used, kind and amount of emulsifier, presence of specific ions, and nature of mechanical agitation.

614. Asphalt-in-water Emulsions. There are two types of asphalt-in-water emulsions: (1) emulsions which coalesce prior to dehydration and (2) those which must dehydrate prior to coalescence. The first type is a labile or "quick-breaking" emulsion; the second is a stable or "slow-breaking" emulsion. Labile asphalt emulsions are used in highway practice for surface dressing or seal coat work, for construction of penetration macadam, and for patching and repairs. Stable emulsions may be used where the emulsion is mixed with the aggregates as in road-mixing and plant-mixing work. Aggregates containing fine dusts require a more stable emulsion than aggregates free from dusts. Stable emulsions are produced by such emulsifying agents as oxides, hydrosilicates, and casein.

"Breaking" of an emulsion may be caused by a number of factors including evaporation of the water, shearing stresses due to rolling and traffic, alteration of interfacial tension, neutralization of charge, and filtration which may take place when the emulsion is brought in contact with aggregate.

615. Tests of Asphalt Emulsions. The tests of asphalt emulsions are different from those for other bituminous materials. The following tests are commonly conducted on asphalt emulsions in the United States.

Water Content. The percentage of water is determined by distillation in a special still or by evaporation in a glass beaker at 163° C. (325° F.), the loss in weight being considered as water content. The asphaltic residue may be tested for penetration, ductility, solubility, and ash content.

Homogeneity of Dispersion. The method consists in passing a given volume of emulsion through a No. 20 sieve, whose wire cloth is wet with a 2 per cent solution of sodium oleate, and in weighing the quantity of bitumen retained on the sieve. The test is designed primarily to detect particles which will not spray readily by pressure through jets.

Storage Stability. After a certain quiescent period, usually 5 days, the water-content test is performed to determine the residue from the bottom 10 per cent of the sample as compared with the residue from the top 10 per cent, and the difference is expressed as the settlement. The test determines coagulation, if such occurs, and also detects poorness of dispersion due to the tendency of large particles to settle in a viscous liquid more rapidly than fine ones. A maximum difference of 2 per cent between the residues of top and bottom layers of the sample is usually specified.

Low-temperature Test. This test involves freezing to a temperature of −17.7° C. (0° F.) for 12 consecutive hours and thawing to laboratory temperature for three cycles. After the third cycle, the emulsion may be homogeneous or may have separated or "broken" into distinct layers which cannot be rendered homogeneous by stirring at laboratory temperature. This test is of value for emulsions which are exposed to weather in cold climates.

Viscosity. Viscosity is ordinarily obtained by the Saybolt Furol viscosimeter. The viscosity of an emulsion must be definite, constant, and suited to the purpose for which it is to be employed.

Rate of Break of Emulsion. The demulsibility test to determine the rate of break of asphalt emulsions is conducted by adding under standardized conditions a weak solution of calcium chloride to the emulsion. This weak electrolyte causes coalescence of the asphalt which is believed to approximate the break that occurs when the emulsion comes into contact with the stone on the road, due to the electrochemical reactivity of the stone. A 0.02 normal solution of calcium chloride is used for the labile type of emulsion and a 0.10 normal solution for the stable type.

Mixing Tests. In addition to the demulsibility test, stable emulsions for use in mixing operations are subjected to actual mixing tests to determine coagulation due to aggregate. Emulsions for coarse aggregate mixtures are tested by mixing for 3 minutes with clean dry crushed stone ranging from ¼ to ¾ inch in size. Note is made as to separation of the bitumen base from the water of the emulsion and also whether the stone is uniformly and thoroughly coated.

Emulsions for fine graded aggregate mixtures including stone dust and soil are tested by mixing with Portland cement which has been sieved through a No. 80 sieve and distilled water. After mixing, the mixture is poured out over a No. 14 sieve and rinsed with water. The weight of coagulated bitumen on the sieve is determined.

An analysis of a typical labile asphalt emulsion is given in Table LXIII.

TABLE LXIII

ANALYSIS OF A TYPICAL LABILE ASPHALT EMULSION FOR PENETRATION TYPE OF CONSTRUCTION

Test	Result
Residue by distillation, per cent	60.2
Residue from distillation:	
Specific gravity, 25°/25° C.	1.007
Penetration, 100 grams, 5 sec., 25° C.	145.
Ductility, 25° C.	100+
Solubility in CS_2, per cent	99.9
Ash, per cent	0.2
Retained on No. 20 sieve	Trace
Settlement in 5 days, per cent	0.5
Saybolt Furol viscosity, 25° C., in sec.	50.
Demulsibility, 35 ml., 0.02 N $CaCl_2$, in per cent	87.5

USES OF BITUMINOUS MATERIALS

616. Pavements and Road Surfaces. The principal use of bituminous materials is in highway construction. Both tar and asphalt are used, but asphalt is used for the higher types of pavements such as sheet asphalt and asphaltic concrete. Sheet asphalt pavements are very common on city streets. Bases are sometimes composed of coarse graded asphaltic concrete mixtures instead of Portland cement concrete, but owing to their flexibility these asphaltic concrete bases should be placed only on stable and well-compacted subgrades.

Bituminous surface treatments may be constructed by the penetration, road-mix, or plant-mix methods. In the penetration method the bituminous material either of hot or cold application type is applied to the aggregate in the road by means of a pressure distributor. In road-mix construction the bituminous material is applied to the loose aggregate on the road by pressure distributors and then it is mixed with the aggregate on the road by means of blade graders. Plant mixing is frequently employed for the preparation of mixtures for bituminous surfaces in order to obtain better control of the proportioning. Both crushed stone and graded gravel aggregates are used for bituminous surface treatments, and many varieties of bituminous materials are employed such as tar and asphalt cements, tar and asphalt cut-backs, road oils, and emulsions. Bituminous macadam is constructed by the penetration method with crushed stone aggregate.

617. Other Surfacing Uses. Runways and taxiways of airports are frequently constructed with bituminous surfaces similar to those for highways. Tennis courts, playgrounds, and sidewalks are often constructed of bituminous mixtures and surfaces. Sawdust and cork are sometimes incorporated in the mixtures.

618. Revetment and Jetty Construction. Reinforced asphalt mattresses are placed at points of severe attack to prevent the underscoring of river banks. Sheet asphalt mixtures with a high percentage of asphalt, reinforced with steel cables and wire mesh, have been successfully used on the Mississippi River.

Hot asphalt mixtures have been used under water to consolidate and waterproof stone jetties. The core of the jetty consisting of large stone fragments is grouted with asphalt mixture which is compacted into place by means of long-handled internal vibrators. The sides of the jetty are waterproofed by a heavy layer of asphalt mixture, and the top of the jetty above water is capped with an asphalt mixture.

619. Waterproofing. One of the most important properties of bituminous material is its impermeability to water, which makes it an excellent material for waterproof protection. Both asphalts and tars are used. Oxidized asphalts are extensively used for waterproofing because of their low susceptibility to temperature changes. Asphalt mastic composed of asphalt cement, mineral filler, and mineral aggregate is also a waterproofing material.

As a protection against dampness, machines, structures, and various classes of merchandise are lined or wrapped with textile fabrics saturated with asphalt.

620. Roofing Felt. Roofing felt composed of felt impregnated with asphalt is used in the form of shingles, tiles, and roll-roofing for protecting the roofs of buildings. It gives good protection against rain, is durable, and relatively cheap. Roofing felt is manufactured by impregnating felt with a relatively soft asphalt and then surfacing with a harder blown asphalt known as a coating asphalt. The coating asphalt gives a rubberlike consistency and weather-resisting qualities. O. G. Strieter has shown by both outdoor and accelerated weathering tests that the addition of fillers increases the durability of coating asphalts in varying degrees depending upon the character, proportion, and particle size of the fillers. The best results were obtained with coatings containing talc, mica, and slate. Less positive results were obtained with coatings containing silica, traprock, dolomite, and limestone.

621. Pipeline Coating. Blown asphalt impregnated with a suitable filler such as finely powdered asbestos is applied as a coating for iron and steel pipes which are buried underground and on the inside of pipes intended to carry water in order to prevent corrosion.

622. Electrical Insulation. Asphalt has a high dielectric strength and is a very good insulator for electricity. Asphalt is poured into junction boxes after the wires have been connected to form a hermetical seal. Electric cables are insulated by tapes made from asphalt-coated fabrics.

623. Uses of Emulsions. The main use of bituminous emulsions is for highway construction and maintenance. Asphalts for these emulsions are generally softer than 100 normal penetration. Labile or "quick-breaking" emulsions are used for dust-laying, seal coats, penetration macadam, and patching and repairing. Stable or "slow-breaking" emulsions are used for road-mix and plant-mix types of construction both with coarse aggregates containing no fine material and with graded aggregates containing dust.

Other industrial applications of bituminous emulsions include impregnation of paper and felt, construction of bituminous layers between courses of Portland cement concrete for waterproofing, curing of Portland cement concrete, coating pipes and metals to prevent corrosion, and use as a binder for cork in insulating walls and ceilings, in place of a solvent in the manufacture of bituminous paints and japans, as ingredient of plastic compositions, and in the manufacture of rubber substitutes.

QUESTIONS

1. Define the following terms: bitumen, asphalt, tar, bituminous material, and bituminous mixture.

2. Describe the occurrence, mining, refining, and characteristics of two lake asphalts.

3. From what petroleum fields in the United States is petroleum asphalt obtained?

4. Describe the manufacture of coal tar and water-gas tar.

5. Describe the principal refining processes employed in manufacturing bituminous materials.

6. Describe the vacuum flash coil process.

7. Distinguish between a fluxed asphalt and a cut-back asphalt.

8. Discuss the common methods of determining consistency of bituminous materials.

9. Explain the meaning of the following terms: normal penetration, specific viscosity, absolute viscosity, poise, loss by volatilization, carbenes, and asphaltenes.

10. Discuss the interpretations of the results obtained in the softening-point and flash-point tests.

11. For what purposes is the ductility test conducted?

12. What are the purposes of conducting solubility tests?

13. A tar has a bitumen content of 90 per cent. Is it a low-carbon or a high-carbon tar?

14. Explain the significance of the Oliensis spot test.

15. What are the effects of oxidation on the properties of asphalt?

16. Does Mexican or California steam-reduced asphalt have the greater susceptibility to temperature change?

17. Explain why viscosity, distillation, and consistency of residue tests are commonly conducted on cut-back asphalts used in highway construction.

18. Distinguish between the characteristics of slow-curing liquid asphalts, and medium-curing and rapid-curing cut-back asphalts.

19. For what classes of road construction are tars used?

20. What is the usual composition range of sheet asphalt paving mixtures?

21. Distinguish between Portland cement concrete and asphaltic concrete.

22. What is the purpose of the binder course for sheet asphalt pavements?

23. What important factors should be considered in the design of sheet asphalt paving mixtures?

24. Describe the Hubbard-Field stability test? What is the significance of this test, and how is it used?

25. How may resistance to cracking of asphalt paving mixtures be investigated?

26. Is it desirable to design sheet asphalt paving mixtures so that they will be excessively high in stability? Explain.

27. Is it desirable to mix asphalt and aggregates for long periods of time in preparing hot asphaltic mixtures for paving purposes? Explain.

28. Describe how paving mixtures should be placed and compacted on the street.

29. Describe the occurrence, characteristics, and uses of rock asphalt.

30. How are bituminous emulsions manufactured and stabilized?

31. Distinguish between labile and "slow-breaking" emulsions.

32. What causes "breaking" of a bituminous emulsion? What laboratory method is used to determine rate of break of bituminous emulsions?

33. Describe briefly the uses of asphalt and tar products in highway construction.

34. Discuss the uses of asphalt in revetment and jetty construction.
35. Describe the manufacture of roofing felt.

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SECTION 8

ORGANIC COATINGS AND PLASTICS

CHAPTER XXII

ORGANIC PROTECTIVE COATINGS

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624. Introduction. Many materials of construction need to be protected from deterioration. A large number of organic compositions are available for this purpose. Organic protective coatings may conveniently be grouped as paints, enamels, varnishes, japans, synthetic finishes, lacquers, and emulsion coatings.

625. Types of Coatings. An ordinary paint consists of finely divided solid particles suspended in a drying oil. The solid particles are known as *pigments,* and many times consist of a mixture of both opaque and semi-opaque substances. The drying oil has the property of forming a tough coating when spread in a thin layer and exposed to air or heat. The aid of chemical catalysts, known as *driers,* may or may not be required. A paint may also contain volatile solvents to reduce its viscosity for the purpose of application. The volatile solvents which are added are called *thinners.* The liquid portion of a paint is referred to as the *vehicle.*

The American Society for Testing Materials defines a paint as a "mixture of pigment with vehicle, intended to be spread in thin coats for decoration or protection, or both." According to the A.S.T.M., a vehicle is defined as "the liquid portion of a paint." Hence, paints would embrace all the various types of pigmented compositions which are used for these purposes. Paints would thus include, as a general group of compositions, enamels, pigmented lacs, lacquer enamels, casein paints, calcimines, flat varnishes and certain of the insulating varnishes containing iron oxides. They would exclude asphalt paints, black japans, and patent leather finishes, where the color is due largely to the soluble ingredients.

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It is generally accepted that an *enamel* is a special kind of a paint, made by suspending pigments in a varnish or a lacquer. The term is often used loosely to include products made from ordinary paint by incorporating varnish and additional pigment. The word is used also for glass coatings, whose films many enamels resemble. The term implies a high gloss, but many enamel paints are now designed to give a semigloss or a dull finish. A much higher degree of dispersion of the pigment in the vehicle is required in enamels than is generally necessary with paints.

Varnishes do not contain any pigment. They include two distinctly different types of coating compositions: (1) *oil varnishes* and (2) *spirit varnishes.* Oil varnishes dry as the result of chemical reactions induced by oxidation, or heat; spirit varnishes dry solely through the evaporation of volatile solvents from the film. A varnish practically always contains a *resin,* except in a few specific preparations such as patent leather varnishes, litho-varnishes, and some of the japans. A resin is an amorphous, vitreous or semi-solid, organic substance, which is insoluble in water, but soluble in organic liquids or in drying oils, or one which can be heated to give a product which is soluble in hot drying oils. The oil varnishes are made by dissolving the resin in heated oil, and cooking the mixture until it has attained the desired properties. Thinners and solutions of driers are added to produce the finished compositions. Spirit varnishes are solutions of one or more resins in volatile liquids. Varnishes composed of alcohol solutions are sometimes classed as *alcoholic varnishes.*

Japans are sometimes classified as a third general type of varnish. There are three kinds of japans: (1) japan driers, (2) black japans and (3) japan colors. These compositions contain little if any resin. Japan driers are solutions of metal soaps (catalysts) in drying oils to which have been added thinners. Japan driers are also known as liquid driers or oil driers. They are not intended for use as varnishes, but only as a simple means for adding catalysts to drying oils, varnishes, and paints by mixing the japan with these products. Black japans are dark oil varnishes containing asphalt, pitch, or similar ingredients. They are made for both air-drying and baking. Their films resemble those of gloss enamels in appearance. Japan colors contain pigments which have been dispersed in a varnish known as a *grinding japan.* They give an unusually hard finish.

Synthetic finishes are solutions of resins which possess drying characteristics similar to those of the drying oils. Fatty acids obtained from drying oils are used in the manufacture of these resins to give them the desired characteristics. These resins are dissolved in volatile solvents to produce the varnishes. Driers are usually added to hasten the drying of the films. The drying can be carried out either in air or by baking. Some of these resins are actually oil varnishes, where the resin has been synthesized in a drying oil. Many of these resins can be incorporated in lacquer-base solutions to give other hybrid types of finishes.

Lacquer is a term which has been used for so many different types of coating compositions that it no longer has any specific significance unless accompanied by a qualifying adjective. The word originally referred to quick-drying varnishes of both the oil-varnish and spirit-varnish types. Later, it was used as a synonym for spirit varnishes; more recently, some authorities have come to use it almost exclusively for compositions containing cellulose derivatives whether or not these products contain resins.

The term might best be reserved for the three entirely different types of products which have always been known exclusively as lacquers. These are: (1) the compositions containing derivatives of cellulose, (2) Chinese or Japanese lacquer, and (3) Indian lacquer. Compositions containing only resins dissolved in volatile solvents had best be called spirit varnishes. Pigmented cellulose derivative compositions are also spoken of as lacquers, but it is best to refer to them as lacquer enamels.

Solutions containing only cellulose derivatives such as cellulose nitrate and cellulose acetate are known as *dopes,* and are classed as a special type of lacquer. They are used for imparting tautness to airplane fabrics and for coating leather. It is customary to add concentrated solutions of cellulose derivatives in the manufacture of lacquers. The solutions are referred to as *lacquer-base solutions* or *dope bases.*

Japanese lacquer is a natural varnish obtained by tapping the tree, *Rhus vernicifera,* which grows in China, Burma, and Japan. Films of this varnish harden rapidly in moist atmospheres but show no drying properties in dry surroundings. The hardened films have very remarkable protective properties. They have been used in this country for coating airplane propellers.

Indian lacquer is a decorative coating of pigmented lac or sealing wax (shellac-rosin composition) where the wood has been coated with the resin without the aid of a solvent. This is done by applying molten lac, or by holding a stick of the resin against the object as it is revolved in a lathe. The heat generated by the friction softens the resin and causes it to adhere to the object. This process is known as "lac turney." *Lac* is the term applied to all resinous products of the Indian scale insect, *laccifer lacca* Kerr. Shellac is only one commercial form of this resin. The word lacquer was derived from lac.

Several materials such as casein, glue, shellac, and rosin are soluble in alkaline aqueous solutions. These solutions can be used either as *aqueous sizes* or *varnishes,* as the vehicle for *aqueous paints* such as casein paints and calcimines, or as media for suspending transparent insoluble materials such as wax. Such wax compositions are generally called wax emulsions, although they are really suspensions since waxes are solid at ordinary temperatures. Lacquer emulsions are emulsified cellulose ester lacquers. The organic solvents used in these compositions are selected so that the water will be the first to evaporate from the film, permitting the final stages of drying to be similar to those of an ordinary lacquer containing cellulose derivatives..

Table LXIV shows the relationship of the various types of coating compositions. This chart is designed to bring out the differences in general drying characteristics which are due to the liquid portion.

PAINT AND ENAMEL

626. Function of Paint. The purposes of paints and enamels may be fourfold. Besides the usual functions of preserving the materials coated and producing a pleasing appearance, paints may also be applied for sanitary purposes and for obtaining better distribution of light. Paints must resist many disintegrating effects such as rain, sand and dirt, chemical fumes, and sunlight in serving as protective coatings. They may be applied for the purpose of combating rot, rust, or the activity of fungi or marine organisms. They serve to fill small cracks and to cover defects, producing a uniform, level surface which is pleasing to the eye. Colored pigments add to the esthetic appeal. The products themselves are antiseptic, and drying films appear to have a limited fumigating effect. Dust and germs in hidden crevices are sealed by the impermeable coatings, and surfaces are obtained which can be kept clean by dusting and occasional washing. Light entering a painted room can be so distributed as to brighten the entire interior. Paint can also be utilized to obtain soothing effects with artificial light. Highway bridge structures can be coated with paints which reflect the light from the headlights of automobiles. Gasoline tanks are usually finished with paints designed to reflect the sunlight and reduce evaporation losses.

627. Types of Failure. The successful use of paints and varnishes as a means for continuous protection depends upon the proper renewal of these coatings. Like any protective coating, paints slowly disintegrate upon exposure, and eventually fail to serve as a source of protection. The predominant type of failure is very important. It determines the type of paint which must be used in repainting.

There are several types of failure: (1) checking or crazing, (2) flaking and scaling, (3) chalking, (4) washing, (5) blistering, and (6) peeling. *Checking* is the formation of numerous, fine, forked, and interlaced cracks in the surface of a finish. The phenomenon is called *alligatoring* when the cracks are comparatively few and large. The paint is said to have *cracked* when the fissures completely penetrate the coating and expose

TABLE LXIV

Classification of Varnishes and Paints

Varnish or Vehicle

- Drying Oil Type (Chemically Reactive)
  - Air-drying Varnishes
    - (1) Vegetable Oils and Drier
    - (2) Emulsified Resin in Drying Oil
    - (3) Resin Chemically Reacted with Oil
    - (4) Asphalt Paints
    - (5) Synthetic Finishes
  - Baking Varnishes
    - (1) Baking Japans
    - (2) Baking Varnishes
    - (3) Synthetic Finishes
    - (4) Baking Lacquers
    - (5) Crackled Finishes
  - Oleoresins
    - (1) Chinese Lacquer
    - (2) Venice Turps
    - (3) Canada Balsam
- Spirit Varnish Type (Chemically Inert)
  - Alcohol Varnishes or Lacquers
    - (1) Shellac Varnishes
    - (2) Shellac Compounds
    - (3) Shellac Substitutes
    - (4) Copal and Rosin Sizes
  - Hydrocarbon Spirit Varnishes
    - (1) Mastic Varnishes
    - (2) Damar Varnishes
    - (3) Asphalt Varnishes
    - (4) Synthetic Finishes
  - Cellulose Derivative Lacquers
    - (1) Cellulose Nitrate or Pyroxylin
    - (2) Cellulose Acetate
    - (3) Bensyl Cellulose
    - (4) Ethyl Cellulose
  - Aqueous Varnishes and Paints
    - (1) Casein Paints
    - (2) Calcimine
    - (3) Shellac Solutions in Aqueous Alkalies
    - (4) Emulsified Wax
    - (5) Glue Sizes
    - (6) Lacquer Emulsions
- Indian Lacquer Type (Applied Molten)
  - (1) Shellac
  - (2) Sealing Wax
  - (3) Rubbing Wax
  - (4) Heavy Metal Soaps
  - (5) Asphalt

the bare undersurface. Cracking usually leads to flaking and scaling, which are the worst forms of failure, since the paint which remains must be removed before repainting. The paint film is said to have *flaked* when it falls off in small pieces, and to have *scaled* if the pieces are large. The degree of failure is judged by the amount of bare surface resulting. Cracking, flaking, and scaling can all be traced to poor adhesion of the film after exposure. Checking is the only major defect noted when the adhesion is good. The loss in elasticity of the film may in part be due to a progressive hardening of the vehicle present in the dried film. Cracking can also be caused by fatigue produced by the differences in expansion and contraction of the paint and the coated surface with variations in temperature and humidity. The loss in adhesion may be caused by water penetrating these cracks and forming substances of poor surface tension at the undersurface of the paint film. Modern air conditioning of homes and buildings has led in many instances to accelerated failures of this type. The paints applied were designed for resisting outdoor exposure only and not for the high humidities produced at the undersurface.

Chalking is caused by a slow erosion of the vehicle at the exposed surface of a paint. The pigment is left as a dust. If it is not washed away by rain or wind, the paint is rated as having heavily chalked. This method of judging paint failure is somewhat misleading, and accounts for the early ultimate failure of films which have been judged as chalking lightly. Many paints are designed to have a definite rate of chalking. This gives an even surface condition for repainting and removes any dirt which spoils the appearance. The reduction in gloss depends upon the degree of chalking. Fading of colored paints may be caused by chalking.

Washing is caused by a chemical reaction within the film which renders the paint soluble in water. The effect may be slight so that only a surface failure occurs, but in some instances it may be so pronounced that the entire film is carried away as a milky suspension.

Blisters are formed by moisture in the wood being drawn to the surface of the film by heat during the drying of the paint film. Where the blisters cover the entire surface, the paint has probably been applied too soon after a rain, or to a damp surface such as wet plaster. Blistering is also caused by water collecting upon the uncoated surface of the wood, by too great an inside moisture content of the wood, or from plumbing leaks. The blisters themselves are usually dry and empty since the vapor escapes rapidly once they are formed. Blisters may also be produced by sap, resin, and essential oils present in the wood, especially around knots. They can be prevented by eliminating the source of moisture and by sealing the wood with a shellac varnish prior to painting.

Peeling may occur without blistering but frequently is produced by the same causes as blistering. It may also be induced by a greasy surface or by the weight of many coats of paint pulling an aged priming film free from the surface.

628. Pigments. The type of failure can be controlled in part by the pigments used in preparing the paint. These ingredients can be divided into three groups depending upon the purpose for which they are added. These groups are: (1) body pigments, (2) colored pigments, and (3) extenders.

The *body pigments* determine to the largest extent the properties of a particular paint. Besides adding body to the paint, they impart opacity, firmness, hardness, imperviousness, and durability to its films. Pigments such as basic carbonate white lead, and red lead, react with the vehicle to a limited extent to form soft soaps which impart toughness and elasticity to paint films for long periods. Paints containing large quantities of white lead, however, show a greater tendency to chalk than other paints. Pure white lead paints are also likely to become badly soiled before chalking has progressed to a sufficient stage to remove the dirt. Checking begins comparatively early, but does not develop into cracks. There is a long interval between checking of pure white lead paints and the beginning of disintegration of the film by crumbling. Zinc oxide, in comparison, forms soaps which cause the paint film to become hard and inelastic. Incorporation of zinc oxide in a white lead paint improves its resistance to soiling, and retards chalking and checking. It increases the chance of failure by cracking, curling, and flaking, however. Large proportions of zinc oxide are incorporated in paints for application in the southern part of the United States where the intense sunlight favors increased chalking. This is done also in order to inhibit the growth of mildew, which is a serious difficulty encountered in warm, damp sections. Other body pigments such as zinc sulfide, lithopone (combinations of zinc sulfide and barium sulfate), titanium oxides, titanoxes (tatanium oxide-barium sulfate or calcium sulfate pigments), and iron oxides are practically inert toward vehicles. They all impart opacity and obscuring properties, and are used to a large extent to dilute the chemically active pigments in a paint without sacrificing opacity. Lead titanate also imparts elasticity.

Certain pigments such as red lead and zinc metal dust have the property of inhibiting the corrosion of iron and steel, even when incorporated in an electrically non-conducting paint film. They are used as the body pigments in anti-corrosive paints to serve as the *priming coat* which is the first one applied. Even when films of these paints are scratched, they protect the exposed metal from corrosion for distances of 1 to 1½ millimeters. These films have good adhesion and are comparatively flexible.

Sublimed blue lead and basic lead chromate have also been recommended as inhibiting pigments, but authorities disagree as to their function and value in this particular respect. Graphite and aluminum flakes give very impermeable films, and hence are useful in protecting metals from corrosion, but they do not show the inhibiting action of red lead or zinc when the films are scratched. Aluminum has the added advantage of reflecting both the infra-red and the ultra-violet rays of the sun, and it thus protects the vehicle from a very serious source of deterioration. Aluminum has little value, however, unless leafing takes place. Leafing is the property of flaked pigments to arrange themselves in an overlapping, horizontal pattern in the paint film. It is this arrangement which produces the excellent impermeability characteristic of paint films containing flakes as the body pigments. Graphite aids in brushing a paint. It is recommended for use with red lead, which is very difficult to brush if the amount of pigment is high, unless the paint is applied in thin coats.

Iron oxides as body pigments vary widely in their anti-corrosive properties. Inhibiting properties of these pigments are probably due to impurities which dissolve in water to give alkaline solutions. This action is also probably characteristic of zinc chromate.

Colored pigments are usually incorporated in paints for their esthetic color-giving properties. Many of them contribute to the durability of the paint films. They also aid in obtaining obscuring effects, but vary widely in permanence and fastness to light.

The colored pigments can be divided most conveniently into two groups, *inorganic* and *organic pigments.* Inorganic pigments include the natural earth colors, synthetic earth colors, certain other oxides, precipitated pigments, blacks, metallic bronzes, and furnace colors. The natural earth colors are prepared from iron oxide ores which have red, yellow, brown, red-brown, or black hues. The synthetic iron oxides are made from soluble iron salts, and have the same general range of hue as the natural oxides. Copper oxide, a brown pigment, and mercuric oxide, a red one, have toxic properties and are used in shipbottom paints to kill the marine growth which attaches itself to the hull of ships. Guinet green is a hydrated chromium oxide, which is used where other pigments of this hue are not suitable. The principal precipitated pigments are the chrome yellows, zinc yellow, cadmium yellows, cadmium reds, iron blues, and chrome greens.

The chrome yellows, as a group, are produced in a wide variety of hues ranging from a very pale canary or primrose yellow to a comparatively deep red. The light colors are mixtures of lead chromate and lead sulfate. The orange pigments consist of lead chromate and the red pigments of basic lead chromates. Zinc yellow (zinc chromate) is manufactured in practically only one shade which is about the same color as a primrose chrome yellow.

Cadmium yellows are usually combinations of cadmium sulfide and barium sulfate, and are often called cadmium lithopones. Cadmium selenide is combined with cadmium sulfide and barium sulfate in producing the cadmium reds.

Iron blues (prussian blues) are essentially ferric ferrocyanides. They have a strong mass color and a green or red undertone. Different types vary quite widely in their properties. Iron blues are combined with chrome yellows to produce the chrome greens.

There are three different types of carbon blacks. Lampblack is made by the incomplete combustion of various oils; carbon blacks (gas blacks) are produced by burning gas; and drop blacks are obtained by calcining of bones. All three types inhibit the drying of paint films. Additional drier is added when they are incorporated.

Metallic bronzes include aluminum pigments. They are made by hammering various metals and alloys first into very thin sheets and then into flakes. They are finally coated with substances such as aluminum stearate to aid in leafing when they are incorporated in a paint.

The furnace colors include the ultramarines, cobalt blue, and sublimed blue lead. The ultramarines are made from a mixture of silica, clay, soda ash, and sulfur. These ingredients are combined in a crucible at high temperatures. Genuine cobalt blue is made in a similar manner from cobalt oxide and alumina. Sublimed blue lead is a fume product of lead sulfide ores. It is a basic sulfate of lead combined with lead oxide, lead sulfide, and other ingredients.

Certain precautions must be observed when more than one pigment is used in a paint, since several pigments tend to react with one another unless they are unusually pure. Pigments containing sulfides, such as zinc sulfide and lithopone whites, cadmium yellows and reds, and ultramarines, are likely to react with pigments containing lead to form black lead sulfide. Thus, sulfide pigments cannot be used, for example, in combination with basic carbonate, or sulfate white lead, or the chrome yellows, reds, and greens. Paints containing lead pigments are also darkened by sulfur fumes or hydrogen sulfide gas. Chrome yellows and greens and iron blues are attacked by alkalies, such as those present in damp plaster. The color of these pigments is changed also by incorporating them with basic pigments, such as basic white leads and chrome yellows. Prussian blues, for example, form the red oxide of iron when mixed with white lead, and chrome yellows are changed to orange by basic pigments. Zinc oxide in contrast can be combined with sulfide pigments without serious effect since it reacts to form white zinc sulfide which has similar properties toward light as the original pigment.

A very large number of different types of dyes are employed in making *organic pigments*. The most common of these are the Hansa yellows, transparent yellow lakes, blue toners, green lakes, toluidine reds, para-reds, lithol reds, bordeaux lakes, madder lakes, and opaque maroons. Few, if any, of these organic pigments even under the best conditions possess the light-fastness of many of the inorganic pigments. For organic pigments, fastness to light varies with the amount of white pigments incorporated with them. They are most widely used for interior paints and enamels where fading is not so serious a factor as it is in outside paints. Many of the organic pigments are superior in resisting alkali and are used in place of iron blues and light chrome yellows when such resistance is required of a paint. They also replace chrome yellows and greens when fading is more desirable than darkening. Pigments sold as *toners* are practically pure dyestuffs or their salts which have been processed for paint use.

Extender pigments when suspended in drying oils have little or no opacity. They include the various forms of barium sulfate, silica, magnesium silicates, clays, gypsum, barium carbonate, calcium carbonates, and mica.

629. Vehicles. The vehicles for paint and enamels, as mentioned previously, consist largely of either drying oils, varnishes, lacquers, or aqueous solutions of binders.

The principal *drying oils* used as paint vehicles are linseed oil, China-wood (tung) oil, perilla oil, oiticicia oil, soya-bean oil, and fish oils from menhaden and California sardines. Small amounts of walnut oil, poppy-seed oil, sunflower oil, and safflower oil are utilized for special purposes. Linseed oil was practically the only common drying oil for this purpose until recent years. China-wood oil is used for waterproof paints and for baking compositions. It is practically never used in its raw state, but must always be cooked in the presence of a suitable drier before incorporating the pigments. The fish oils are especially suitable for paints which must withstand high temperatures. They give the best results in combination with China-wood oil. Perilla, oiticicia, and soya-bean oils are generally blended with other oils. Various attempts are now being made to find a suitable substitute for China-wood oil, owing to the occupation by the Japanese of certain areas of China, the major source for this material.

The raw oils are now refined by various chemical processes. Treatment with alkali to give *alkali-refined* oils is common. The properties of drying oils for certain purposes can also be modified by heating. The *boiled oils* contain driers and have been heated in contact with air, whereas *blown oils* have been treated with a plentiful supply of air in the presence of a minimum of driers, and *polymerized or bodied* oils have been heated in the absence of air or with a minimum of oxidation. *Flattening oils* contain aluminum stearate to reduce the gloss of their films.

Oil varnishes are sometimes added in preparing a paint to increase the gloss, hardness, durability, and wearing qualities. Addition of glyceryl phthalate resin varnishes is recommended particularly for paints to be used in the tropics where the life of a paint film is of extremely short duration. It has become recent practice to call these compositions *fortified paints*. Enamels in contrast contain varnishes as the major component of the vehicle.

Thinners are added to the oils and varnishes in paints and enamels to lower the viscosity of the compositions so that objects can be properly coated by brushing, spraying, or dipping. The addition of thinners improves the flowing and leveling qualities of a paint as well as increasing the penetrating properties which are essential for good adhesion between coats. Large amounts of thinners deaden the gloss, producing an effect known as *flattening*. The common thinners are turpentine, solvent naphtha, and various petroleum thinners of low-boiling range. Kerosene should always be avoided.

Driers are added to accelerate the oxidation of the oil and the chemical reactions known as *polymerization,* which are responsible for the drying of the films. Polymerization reactions produce chemical compounds of the same composition but differing in molecular size and weights. The molecular weights of *polymers* are multiples of those of the original compounds. The principal driers are the cobalt, manganese, and lead salts of fatty acids, rosin acids, or naphthenic acids. The general practice today is to add solutions of these catalysts to the paint. Earlier practice was to prepare a japan drier, or to add the metal oxide or acetate to the varnish during cooking. Driers prepared from linseed oil or linseed fatty acids are known as *linoleates;* those from China-wood oil as *tungates;* those from rosin, *resinates;* and those from the naphthenic acids obtained from petroleum, *naphthenates.*

Lacquer vehicles generally consist of a cellulose derivative, such as cellulose nitrate, and resins of one or more types dissolved in a mixture of organic liquids. The liquid constituent should contain one or more solvents for each of the solid components. It should also contain a *diluent* or thinner, which may be a non-solvent for some or all of the solids. The organic liquids including the diluents are selected to maintain a homogeneous system throughout the entire drying of the lacquer film. The pigment, of course, is not soluble in the vehicle but is maintained as a uniform suspension as in other paints. *Plasticizers* are also incorporated to increase the flexibility and ductility of the films. Most of the plasticizers are non-volatile organic liquids. A very few are solids.

Aqueous vehicles used for cold-water paints are of two general types. The whitewash type, or *calcimine,* contains slaked lime, salt, flour, and glue, with whiting (calcium carbonate) as the pigment. Calcimines cannot be washed without the danger of removing them. Enormous quantities are used each year for cellars, barns, and ceilings in houses. The other types are washable. They are known as *casein paints,* and contain casein, lime, emulsified drying oils, salts, and antiseptics dissolved in water to form the vehicle for these paints. Pigments are limited to those which are alkali resistant since vehicles contain dissolved lime. Exterior casein paints also contain emulsified alkyd resins to impart weather resistance. The cold-water paints are sold in both dry form and as ready-mixed paints. They are relatively inexpensive and have good covering properties and light reflection.

630. Types of Paints. A single paint seldom possesses all the necessary properties to give the most satisfactory results in protecting wood or metal. Hence, a system of different paints is generally employed for this purpose, where each coating has been designed to serve a particular function in these protective systems. The various coatings are known as *primers, secondary coats,* and *finish coats.* Paints are evaluated by exterior exposure tests. Coated panels are mounted upon test fences in different parts of the country where they will be subjected to all types of conditions. These tests are then correlated with actual service tests before any final conclusions can be drawn in regard to a particular paint or system. Since paints vary widely in their composition, the most convenient method for classifying individual ones is according to their use. The pigment composition, pigment concentration, and type of vehicle are the most important factors in determining the properties of a paint. However, the manner in which paints are applied and the condition of the surface at the time of repainting have so important an influence upon the type of results obtained that few manufacturers will assume full responsibility for the behavior of their paints.

Exterior House Paints. It is now generally accepted that paints prepared from manufactured pastes or ready-mixed house paints give better results than those prepared by the older practice of the painter incorporating his own pigments by hand. It has been shown that any minute void caused by improper wetting of a pigment by the vehicle is a potential point for failure of the film when it is placed under stress, as paint films continuously are, in service.

The most common ready-mixed house paints now upon the market for exterior use contain a mixture of body pigments. A few pure white lead paints are the only exceptions. Most of the paints contain mixtures of white lead and zinc oxide to which have been added either transparent pigments or inert opaque whites. The better-grade paints containing transparent pigments limit the amount of these pigments to 20 per cent by volume. The dark-colored paints contain greater proportions of inactive pigments than the light tints and whites. The addition of inert pigments reduces the amount of cracking, flaking, and curling, but tends to stimulate erosion if transparent pigments are employed. The general trend at the present time is to replace the transparent pigments with the opaque zinc sulfide and titanium oxide pigments. Paints containing zinc sulfide may have as much as 60 to 90 per cent inerts. Most of these paints, however, are the manufacturer's second grade of paint. Zinc sulfide unlike the other inactive white pigments does not restrain checking, and it stimulates crumbling of the films. Large additions of zinc oxide to counteract these tendencies lead to curling and flaking. The lead present in paints containing large amounts of zinc sulfide is usually added as a leaded zinc oxide pigment. Titanium oxide paints also contain a large proportion of the inert whites. They generally are lower in zinc oxide than the other paints. The lead content varies widely, and a few are lead-free. Addition of titanium pigments in general retards erosion and eliminates checking. Cracking is postponed and is accompanied with little curling or flaking. If repainting is neglected, as it used to be, cheap paints sometimes give better results than high-grade paints improperly handled.

Formerly, raw linseed oil was the only vehicle in paints, but it is now becoming customary to add small proportions of moderate-bodied oils without imparting properties of an enamel. These products, however, differ from true paints in the composition of pigments, the pigment concentration, and the amount of thinner added. Most of them contain the high-opacity pigments, such as titanium oxide and zinc sulfide. They have been termed *enamelized paints* to distinguish them from the older types of paint. The recent introduction of phenolic and alkyd resins into paints gives a second group of enamelized paint known as *fortified paints.*

It is possible to use the same type of paint for all coats in painting houses by varying the total amount of pigment and the thinner. With a three-coat system, the priming coat usually contains from 20 to 25 per cent by volume of pigment, the second coat from 35 to 40 per cent, and the finish coat from 25 to 32 per cent. Two-coat systems have from 25 to 32 per cent of pigment in each coat. Where different paints are used, aluminum paint makes an excellent primer.

Barn Paints. Large quantities of iron oxide paints are used in agricultural districts for painting barns and similar buildings where the color is not so objectionable as it would be upon a house. These paints are made by suspending the cheaper mineral earth and synthetic iron oxides in linseed or mixed oils and diluting with a petroleum thinner. Gloss oil driers made from rosin heated with litharge are sometimes added to hasten the drying. House paints are also used for these purposes.

Floor Paints. Paints designed to withstand considerable abrasion such as encountered upon floors are made by suspending the usual body pigments, and barytes or silica, in linseed oil. The paste so prepared is then mixed with a durable mixing varnish. The inerts and varnish produce films which are more resistant to wear than ordinary paints.

Enamel Paints. Enamels are made by suspending pigments in varnishes or heavy-bodied drying oils. In consequence, they have greater body than paint, and generally different leveling properties. They must be applied to very smooth surfaces or the imperfections will be evident if a gloss type of enamel is used. The flat and semi-gloss types have largely replaced the gloss finishes because of the better lighting effects obtained. Lithopone paints are often applied as primers for this type of finish.

Flat Wall Paints. Calcimine, casein paints, and oil paints containing a flattening agent such as aluminum stearate or diatomaceous silica, are used as wall paints. Colored pigments incorporated with the body pigments should be alkali resistant for this type of paint. When applying the oil type of paint, care should be taken that the plaster has dried or peeling will result.

Plastic Paints. Paints for producing various rough plastic effects upon walls have the property of liquefying when subjected to agitation and revert to a more or less rigid jelly when allowed to come to rest. This phenomenon is known as *thixotropy.* This property can be imparted to a paint by favoring flocculation of the pigment through controlled wetting properties, or by the introduction of metal soaps by reactions of special pigments (highly reactive lithopones), or by the addition of fatty acids which will react with one of the pigment constituents.

Paints for Structural Steel. The corrosion of metals is caused by electrochemical reactions which take place in the presence of condensed moisture containing dissolved gases. Hence, in using paint to prevent corrosion, the paint system should be as impervious as possible to prevent these gases from reaching the metal. The priming coat usually contains a large proportion of inhibiting pigments such as previously described to protect the metal against imperfections in the coating. Red lead of high purity is the most popular pigment for this purpose, but red lead paints produce films which have poor wearing properties and should be finished with paints which do wear well. As it is not customary to use finish coats in the interior of ships, care should be taken that the edges of all hatches and manholes which will be subjected to wear should be coated with another type of anti-corrosive paint. The metal should be cleaned of all scale, rust, and grease before painting.

Marine Paints. Ships below the water line are generally coated first with an anti-corrosive paint and then finished with a quick-drying paint containing copper and mercuric oxides to kill the marine growth which attaches itself to the bottom of the ship. The paints are usually designed to erode slowly, thus continuously freeing the surface. Zinc and iron oxides ordinarily constitute the body pigments.

Aluminum Paint. The most important feature in the use of aluminum paint is that the pigment shows a maximum leafing in the dried film. Best results are obtained when the paint has not stood too long after having been mixed. Bodied or blown oils, and varnishes, generally serve as the vehicles, although a wide variety of other vehicles are used for special purposes. The most satisfactory exterior paints are made by incorporating 20 to 30 per cent by weight of pigment in a gallon of spar varnish containing some tung or perilla oil.

Paints for Concrete and Cement. A highly waterproof vehicle is also required in paints prepared for coating concrete and cement. The types of pigments used are similar to those for exterior house paints. The surface of the concrete is usually washed with a solution of zinc sulfate to neutralize the hydrated lime which is present before applying these paints.

Lacquer Enamels. These finishes give hard, flexible films. They are extensively used for coating various types of metal work, such as hardware, electric-light fixtures, machinery, and automobiles. They are also satisfactory for high-grade furniture. Lacquer enamels have the advantage of drying very rapidly. Special types are used for baked finishes. They must be used with great discretion over other types of finishes.

Stains. Wood stains may be divided into four classes: namely, (1) water stains, (2) oil stains, (3) spirit stains, and (4) chemical stains. Many oil stains contain pigments and are in several respects essentially highly diluted, penetrating paints. Other types of oil stains contain preservatives, while a third group of oil stains contain only soluble dyes. Water and spirit stains also contain only dyestuffs dissolved either in water or a suitable organic liquid. With chemical stains, the color is produced by reactions within the wood. Stains are used for the esthetic effects which can be obtained, and also for obtaining greater durability by means of the preservative types.

Industrial Paints. Many other types of paints besides those described are found in industry. Here, there is a great demand for paints of special properties such as refrigerator paints, heat-resisting paints, fire-resisting paints, crackled finishes, and novelty coatings. All types of pigments and vehicles are used in manufacturing these paints. Many are made to meet rigid individual specifications.

VARNISHES

631. General. Varnishes, like paints, are used for so wide a variety of purposes that no single varnish is suitable for all. Previously, the oil length of a varnish was the most important factor in determining the properties of drying oil varnish film, but since the introduction of reactive types of synthetic resins into varnish manufacture, oil length is not always so important as it was formerly. In general, a greater proportion of oil favors greater flexibility of the films and more resistance to weathering, whereas large percentages of resins give finishes which are harder and capable of being sanded and polished. *Oil length* is defined as the number of gallons of drying oils added to 100 pounds of resin in the manufacture of a varnish. Losses during the heating of the resin or during cooking are neglected. Few natural resins are soluble in drying oils, and consequently they must be heated (*run*) until they have lost by volatilization about 20 per cent by weight before they can be combined with the oils. This is not true with synthetic resins which can be incorporated directly with the oil.

The natural resins for oil varnishes are the copals, the kauri copals, the dammars, and rosin. The synthetic resins include phenolic resins of many types, various modifications of alkyd resins, cumars, and ester gum (glycerol ester of rosin). There are also a large number of hybrid types of synthetic resins, while ester gum is a common constituent of many of the cheaper phenolic resins. Natural and synthetic resins which are soluble in organic liquids are also used in the manufacture of spirit varnishes and cellulose ester lacquers. Asphalt and rubber are employed in making certain types.

632. Types of Varnishes. Varnishes of different compositions are frequently used for similar purposes. A convenient method is to divide them into two classes: (1) architectural varnishes, and (2) industrial varnishes. The first group includes cabinet or rubbing varnishes; varnishes for floors, trims, and doors; flat varnishes; exterior varnishes; marine varnishes; cement and stucco sealers; and waterproofing compounds. The second group comprises an even wider variety of compositions which may be applied to different surfaces by one of several methods, such as brushing, dipping, tumbling, and spraying. Several varnishes are made specially as vehicles for enamels and aluminum paint.

Rubbing Varnishes. These varnishes are from 12 to 25 gallons in length, and can be made from copal resins, China-wood oil, and linseed oil cooked to a hard pill. Cellulose nitrate lacquers containing large amounts of resins have now almost entirely replaced this type of varnish, especially where the varnish is applied in a factory.

Floor Finishes. Varnishes of a number of different types are used for this purpose. They include oil varnishes from 8 to 50 gallons in length, spirit shellac varnishes, cellulose nitrate lacquers, and wax compositions. Shellac gives the hardest finish and has the best appearance. It is also the easiest to refinish. Long oil varnishes have the greatest durability, which is due to toughness rather than hardness. Wax finishes have to be continuously renewed and are slippery, but are quite popular at the present time since they retain the natural color of the wood.

Trim and Door Finishes. These varnishes range from 15 to 25 gallons in length, and the resin used depends almost entirely upon cost. Ester gum is employed for the cheap varnishes, while synthetic resins are used for the quick-drying higher-priced products.

Wall sizes consist of manila copal-rosin spirit varnishes, shellac varnishes, cheap ester gum drying oil varnishes, or cumar oil varnishes. The last gives films which are quite resistant to lime.

Enamel Vehicles. These are made with copal, ester gum, or synthetic resins cooked with either pure linseed oil, or mixtures of linseed oil and China-wood oil. They are from 40 to 75 gallons in length.

Flat varnishes are from 12 to 18 gallons in length. They can be made by blending short China-wood varnishes with processed linseed, perilla, soya-bean, and fish oils.

Exterior and Marine Varnishes. These varnishes are also known as *spar varnishes.* They are made with various resins and are from 35 to 75 gallons in length. The best varnishes are those made with reactive resins, such as the 100 per cent phenolic resins, and China-wood oil.

Cement and stucco sealers should be alkali resistant. They are usually short cumar-wood oil varnishes or cumar spirit varnishes.

Waterproofing compounds are either metal stearate solutions or wax emulsions.

Industrial Finishes. These varnishes are as varied as they are numerous. The choice of varnish is usually a matter of either custom, cost, or personal preference of the user. Varnishes for wood include those used for furniture, caskets, and toys. Those for metal cover the varnishes for metal furniture, automobiles, railroads, ships, and tin decorating. Other industrial varnishes include insulating varnishes; varnishes for impregnating and coating paper; coatings for rubber cloth, imitation leather, linoleum, and composition wallboard; and acid-resisting varnishes for concrete tanks and storage batteries. Many of these varnishes are of a quick-drying or baking type as might be expected with mass-production methods.

QUESTIONS

1. List the different types of components of each of the following: an ordinary paint, an enamel, a black japan, an oil varnish, a spirit varnish, a synthetic finish, a cellulose ester lacquer, a casein paint, a calcimine, and a lacquer enamel.

2. What is meant by each of the following terms: a resin, a pigment, a thinner, a drier, a vehicle, a plasticizer, a dope, a lacquer-base solution, a plastic paint, and a toner?

3. For what purposes is paint used? Give examples.

4. What are some of the factors which cause organic protective coatings to disintegrate? Describe the different types of failure of paint films. How can each be controlled?

5. What are the different general types of pigments? Give several examples of each type. What factors should be considered in selecting pigments for incorporation in vehicles?

6. Name the different types of vehicles. What are the principal drying oils, and for what purpose is each used?

7. Define: a blown oil, a boiled oil, a refined oil, a bodied oil, and a flattening oil.

8. Describe what is meant by (*a*) the oil length of a varnish, (*b*) running of a natural resin, (*c*) an ester gum, (*d*) polymerization, and (*e*) thixotropy.

9. Why is more than one coat of paint used to protect a bare surface? Why are different paints frequently selected for each coat? What is meant by a paint system?

10. How are paints evaluated?

11. What type of paint would you recommend for each of the following purposes: the exterior of a wooden house, a brick wall, a large gasoline tank, a steel bridge, a cellar, a kitchen stove, a barn, stair treads, a cold-water pipe, and a timber pier?

12. What type of varnish would you recommend for each of the following: a front door, the deck of a boat, a parquet floor, a bowling alley, a desk, a porch, a concrete tank, a steam pipe, an airplane propeller, and a pine-wood ceiling?

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CHAPTER XXIII

ORGANIC PLASTICS

By Wm. Howlett Gardner

633. Introduction. It is now generally recognized that organic plastics comprise an important group of materials of construction. Many of these plastic substances have combinations of properties which cannot be duplicated by other materials. Articles made from them have the general characteristics of lightness in weight, excellent mechanical and electrical properties, and a high degree of permanence and beauty of finish. They can be produced with precision and are easy to fabricate. Many finished articles can be turned upon a lathe, sawed, punched, and drilled to suit needed purposes. Molded parts may contain metal inserts, since most of these plastics are inert toward such materials. Several of the fabricated compositions are extremely resistant toward chemicals and toward organic liquids. Certain others are used for their special properties toward light.

Summaries of some of the properties of molded commercial compositions as reported by various manufacturers[1] are given in Tables LXV and LXVI. These tables are included only for general comparative purposes, and should not be used for engineering design since there are several kinds and grades of each individual type of plastic. The assistance of manufacturers and of molders[2] should be sought before making a final choice of plastic material and of the design to be used.

634. Classifications. An organic plastic is a material exhibiting characteristics of plasticity which has organic substances as the binder. The term plastic is rather broadly used, and is applied to any article made from plastic materials even if it has been transformed into an infusible (resinoid) state. All organic plastics contain a binder which imparts the plastic properties to the composition. Many plastics contain in addition a filler which is an inert extender. Filler is added to impart hardness, strength, and other desirable properties. Inert dyes and pigments are

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[1] The Bakelite Corp.; Carbide and Carbon Chemicals Corp.; The Celluloid Corp.; Cutler-Hammer, Inc.; Durite Plastics; Hercules Powder Co.; Röhm and Haas Co.; and E. I. du Pont de Nemours & Co.

[2] A list of trade names and addresses of producers and molders may be found in *Modern Plastics*, v. 16, 1938, pp. 299-302.

TABLE LXV

MECHANICAL PROPERTIES OF MOLDED COMPOSITIONS

Type of Material	Tensile Strength, lb. per sq. in.	Impact Strength Notched Bar, ft-lb. per in.	Modulus of Rupture, lb. per sq. in.	Modulus of Elasticity, lb. per sq. in.	Specific Gravity	Heat Distortion, degrees C.	Hardness	Coefficient of Linear Expansion per degree C.
Phenolic laminated, paper base	6000–13,000	0.8–2.4 C[1]	13,000–20,000	1.0–2.0 $\times 10^{6}$	1.34–1.55	100–140	85–125 R[3]	20– 50 $\times 10^{-6}$
Phenolic laminated, canvas base	8000–12,000	1.6–10.4 C	12,000–19,000	1.0–2.0 $\times 10^{6}$	1.34–1.55	100–140	95–115 R	30– 70 $\times 10^{-6}$
Phenolic molded, woodflour filled	6000–11,000	0.26–0.50 C	8000–15,000	0.8–1.5 $\times 10^{6}$	1.25–1.52	120–140	95–120 R	35– 80 $\times 10^{-6}$
Phenolic molded, cellulose filled	6000–11,000	0.40–0.80 C	8000–15,000	0.8–1.5 $\times 10^{6}$	1.32–1.48	120–140	95–115 R	35– 80 $\times 10^{-6}$
Phenolic molded, fabric filled	6000–8000	0.80–6.0 C	8000–13,000	0.8–1.5 $\times 10^{6}$	1.35–1.40	120–140	90–115 R	35– 80 $\times 10^{-6}$
Phenolic molded, mineral filled	5000–9000	0.26–1.0 C	8000–18,000	1.0–5.0 $\times 10^{6}$	1.70–2.05	120–150	100–120 R	25– 50 $\times 10^{-6}$
Cast phenolics	3000–7000	0.30–0.50 C	3000–14,000	0.25–0.75 $\times 10^{6}$	1.26–1.70	40– 80	70–110 R	70–160 $\times 10^{-6}$
Phenolic molded, transparent	8000	....	1600	....	1.27	107	....	....
Furfuryl-phenol molded, woodflour filled	5000–12,000	1.0–6.5 I[2]	10,000–16,000	....	1.3–1.4	131	35–40 B[4]	30 $\times 10^{-6}$
Furfuryl-phenol molded, asbestos filled	4000–12,000	1.0–6.0 I	8000–14,000	....	1.6–2.0	136	44–46 B	20 $\times 10^{-6}$
Furfuryl-phenol molded, fabric filled	5000–10,000	20–39 I	10,000–16,000	....	1.3–1.4	....	30–35 B	....
Furfuryl-phenol laminated, paper base	10,000–20,000	5.0–20 I	20,000–30,000	....	1.3–1.4	....	....	....
Furfuryl-phenol laminated, cloth base	9000–12,000	10.0–50 I	....	....	1.3–1.4	....	....	....
Urea molded	9000–12,000	0.28–0.36 C	10,000–14,000	1.2–1.9 $\times 10^{6}$	1.45–1.55	95–130	110–125 R	....
Polystyrene molded	5000–7000	0.40–0.60 C	6000–8000	0.40–0.60 $\times 10^{6}$	1.05–1.07	75–80	82–92 R	65– 75 $\times 10^{-6}$
Acrylate molded	4000–8000	0.3–4.0 C	9000–16,000	0.4–0.6 $\times 10^{6}$	1.18–1.19	51–60	18–20 B	80 $\times 10^{-6}$
Methyl methacrylate molded	9000–12,000	0.2–3.0 C	12,000–14,000	....	1.18–1.20	60–135	17–20 B	70– 90 $\times 10^{-6}$
Cellulose nitrate molded	4900–8500	10–11.5 I	5000–8000	0.2–0.4 $\times 10^{6}$	1.35–1.60	71–91	7–12 B	120–160 $\times 10^{-6}$
Cellulose acetate molded	4000–5000	1.7–3.0 C	5000–7000	0.20–0.40 $\times 10^{6}$	1.27–1.63	50–80	85–120 R	140–160 $\times 10^{-6}$
Ethyl cellulose	5000–9000	3.2–9.6 I	....	0.3 $\times 10^{6}$	1.14	100–130	....	....
Shellac	900–2000	....	....	....	1.1–2.7	66–90	....	....
Cold-molded composition	700–1700	1.5–4.5	3500–7800	....	1.9–2.12	182–260	....	....
Hard rubber	1500–10,000	0.5 I	....	0.33 $\times 10^{6}$	1.12–1.80	....	31 B	80 $\times 10^{-6}$

[1] C = Charpy. [2] I = Izod. [3] R = Rockwell. [4] B = Brinell.

TABLE LXVI

Electrical Properties of Molded-Compositions

Type of Material	Power Factors			Dielectric Constant			Loss Factor			Resistivity, megohm-cm.	Dielectric Strength Step Test, volts per mil
	60 cycles per second	1000 cycles per second	10^6 cycles per second	60 cycles per second	1000 cycles per second	10^6 cycles per second	60 cycles per second	1000 cycles per second	10^6 cycles per second		
Phenolic laminated, paper base	0.02–0.15	0.02–0.10	0.02–0.06	4.5–6.5	4.5–6.0	4.0–5.5	0.1–1.0	0.1–0.6	0.10–0.30	2×10^6–1×10^8	400–600
Phenolic laminated, canvas base	0.05–0.30	0.05–0.20	0.04–0.10	5.0–9.0	4.5–8.0	4.0–6.0	0.25–2.0	0.15–1.0	0.15–1.0	3×10^5–4×10^7	250–400
Phenolic molded, woodflour filled	0.02–0.30	0.02–0.15	0.035–0.08	4.5–10.0	4.5–10.0	4.0–8.0	0.10–3.0	0.20–1.5	0.15–0.80	10^4–10^6	200–300
Phenolic molded, cellulose filled	0.05–0.30	0.04–0.15	0.04–0.10	4.5–10.0	4.5–10.0	4.0–8.0	0.25–3.0	0.20–1.5	0.15–1.0	10^4–10^5	200–300
Phenolic molded, fabric filled	0.05–0.30	0.04–0.15	0.04–0.10	4.5–15	4.5–15	4.0–10	0.25–4.5	0.20–2.0	0.15–1.0	10^3–10^5	200–300
Phenolic molded, mineral filled	0.020–0.50	0.01–0.20	0.005–0.10	4.5–20	4.5–15	4.0–10	0.10–4.0	0.045–3.0	0.020–1.0	10^3–10^8	200–375
Cast phenolics	0.070–0.50	0.030–0.30	0.04–0.13	7.0–30	6.0–25	5.5–15	0.70–16.0	0.20–4.0	0.20–2.0	10^4–10^7	120–300
Phenolic molded, transparent	0.06	0.04	0.019	5.5	5.0	4.5	....	....	....	7.5×10^5	325
Furfuryl-phenol molded, woodflour filled	....	0.04–0.15	0.01–0.06	....	4.0–8.0	6–7.5	....	....	....	10^{10}–10^{12}	400–600
Furfuryl-phenol molded, asbestos filled	....	0.1–0.15	0.06–0.15	....	4.5–20	5–18	....	....	....	10^9–10^{11}	200–500
Furfuryl-phenol molded, fabric filled	....	0.08–0.2	0.05–0.08	....	4.5–6	6	....	....	....	10^{10}	200–500
Furfuryl-phenol laminated, paper base	....	....	0.15–0.48	....	4.5	....	....	....	....	....	900–1800
Furfuryl-phenol laminated, cloth base	....	....	0.41–0.64	....	4.5	....	....	....	....	....	300–700
Urea molded	0.050–0.13	0.035–0.07	0.035–0.040	8.0–10	8.0–9.0	6.9–7.5	0.40–1.2	0.28–0.65	0.24–0.30	1–10×10^6	275–325
Polystyrene molded	0.0001–0.0002	0.0001–0.0002	Under 0.0002	2.6	2.6	2.6	0.00026–0.00053	0.00026–0.00053	Under 0.0005	Over 10^{10}	500–525
Acrylate molded	0.05–0.06	....	....	3.4–3.6	....	....	....	....	....	1.0×10^{15}	500
Methyl methacrylate, molded	0.06–0.08	....	0.02	4.0–4.4	....	2.8	....	....	....	1.0×10^{15}	480
Cellulose nitrate, molded	0.062–0.149	....	0.07–0.09	6.7–7.3	....	6.2	....	....	....	2–30×10^{10}	660–780
Cellulose acetate, molded	0.03–0.05	0.035–0.07	0.035–0.07	4.5–7.0	4.5–6.5	4.0–4.5	0.13–0.30	0.15–0.40	0.15–0.40	10^6–10^8	300–350
Ethyl cellulose, molded	0.03–0.06	0.025	....	2.6–2.9	3.9	....	....	....	....	....	1500
Shellac, molded filled	0.004–0.018 P[1]	....	....	3–4	....	....	0.016–0.16 P	....	....	10^8–10^{16}	200–600
Cold-molded composition	0.2	....	0.07	15.0	....	6.0	....	....	....	1.3×10^{12}	85–100
Hard rubber	....	....	0.003–0.008	2.8	2.9–3.0	3.0	....	....	....	10^{12}–10^{15}	250–1000

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[1] P = Paper filled.

added for their decorative effects. Organic plastics may be divided into three general groups upon the basis of their behavior toward heat.

Thermoplastic or *heat non-convertible* compositions are those which remain permanently soft at elevated temperatures. It is necessary to cool them before they assume a rigid form. These materials can be shaped and reshaped by means of heat and pressure.

Thermosetting or *heat convertible* compositions are transformed into infusible products upon heating. These compositions are thermoplastic when first heated under pressure, but rapidly assume a permanent rigid state as chemical changes take place in the binder. Fabricated articles of this type of composition can be ejected from the molds without cooling.

Chemically setting compositions are those which harden by the addition of a suitable chemical to the composition just before molding or by subsequent chemical treatment following fabrication. These procedures are necessary with certain binders, or the composition would become infusible before it is formed.

The types of organic plastics which belong to each group are shown in Table LXVII. The synthetic binders which are designated as *addition polymerides* are mixtures of polymers, which have been formed by addition of like molecules. Those which are classified as *condensation polymerides* have been formed by chemical reactions in which two or more different molecules combine with the separation of water or other simple substances in the formation of these resins.

635. Types of Binders. Resins made from phenol (carbolic acid) and formaldehyde are the most widely used binders for organic plastics. Articles prepared from these *phenol-formaldehyde* or *phenolic compositions* are characterized by their relative permanence, which is probably a result of their infusibility and hardness. They have excellent mechanical and electrical properties, and are highly resistant to heat. The cellulose-filled products, for instance, are unaffected by temperatures up to 150° C. (302° F.), and certain mineral-filled materials will completely resist temperatures as high as 235° C. (455° F.) for short periods. These products are also highly resistant to water, oil, common solvents, mild alkalies, organic acids, and dilute mineral acids. They are disintegrated by strong sulfuric and nitric acids and by concentrated caustic solutions. Compositions show very small shrinkage upon molding, so mechanical parts can be made in this manner with a fairly high degree of precision. Rapid setting (quick-curing) materials make it possible to obtain very high rates of production in the fabrication of these articles. Special cutting tools have been introduced for the machining of these materials.

Phenol-formaldehyde resins are combined with various percentages of different fillers and fabrics to give a variety of types of plastic compositions. The compositions may be divided into five general classes:

TABLE LXVII

CLASSIFICATION OF THE COMMONER ORGANIC PLASTICS

Plastic Binder

- Thermoplastic Group
  - Natural
  - Synthetic
    - Resin Binders
      - (1) Rosin
      - (2) Copals
    - Asphaltic Binders
      - (1) Asphalts
      - (2) Bitumens
      - (3) Gilsonite
      - (4) Glance Pitch
      - (5) Pitches
        - (a) Stearin Pitch
        - (b) Wood Pitch
        - (c) Coal Tar
        - (d) Coke-oven Pitch
        - (e) Water-gas Pitch
    - Cellulose Derivatives
      - (1) Pyroxylin (Cellulose Nitrate)
      - (2) Cellulose Acetate
      - (3) Benzyl Cellulose
      - (4) Ethyl Cellulose
    - Rubbers
      - (1) Rubber
      - (2) Chlorinated Rubber
      - (3) Treated Rubber
      - (4) Polysulfide Rubber
    - Addition Polymerides
      - (1) Vinyl Chloride
      - (2) Chlorovinyl Chloride
      - (3) Vinyl Acetate
      - (4) Vinyl Ethers
      - (5) Styrene (Styrol)
      - (6) Acrylates
      - (7) Acrolein
      - (8) Methyl Methacrylate
      - (9) Cumarone-indene
      - (10) Butadiene Rubber
    - Condensation Polymerides
      - (1) Glycol Modified Alkyds
      - (2) Acid Catalysed Phenol-formaldehyde
- Semi-thermosetting
  - (1) Shellac
- Thermosetting Group
  - Addition Polymerides
    - (1) Polyvinyl Types of Resins
    - (2) Chloroprene Rubber
  - Condensation Polymerides
    - (1) Phenol-formaldehyde
    - (2) Cast Phenolics
    - (3) Transparent Molded Phenolics
    - (4) Resorcinol-formaldehyde
    - (5) Acroite (Glycerin-phenol)
    - (6) Phenol-furfural
    - (7) Urea and Thiourea-formaldehyde
    - (8) Casein (Soya)-formaldehyde
    - 9) Sulfonamide Resins
- Chemical Setting Group
  - (1) Harvel Resins
  - (2) Cold Molded Plastics
  - (3) Vulcanised Rubber
  - (4) Casein (Milk)

namely, cellulose-filled compositions, mineral-filled compositions, molding sheet, impact-resistant materials, and special materials. The first class is used for molding where a high finish and precision are desired. Wood flour is usually the filler employed. The molded articles have high dielectric strength, mechanical strength, and lightness, and are used extensively by the airplane, automotive, and railroad industries where weight is an important consideration in design. The second class of compositions may have asbestos as the filler. These compositions are selected for articles designed to resist chemicals, heat, and exterior exposure. They are extensively used for outdoor electrical insulators, but are not suitable for high-voltage transmission where arcing may produce carbonization with this type of plastic. Molding sheet, the third class, is made by impregnating paper with phenolic resins. It is brittle when cold but can be softened by heat and cut into sizes suitable for molding. The sheets are 18 inches long, 40 inches wide, and $\frac{3}{16}$ inch thick. It is employed for molding complicated forms where a more plastic material is needed than can be obtained with the first two classes of compositions. Molded articles of these compositions are slightly inferior in mechanical properties to those made with the other phenolic compositions. Impact-resistant articles, the fourth class, are made from impregnated paper and fabric fillers, built up in layers. These are known as *laminated plastics.* The composition can be hot-pressed into plates and other simple forms. They are widely used for making articles such as heavy-service gears where unusual toughness and strength are required. The special types, the last class, are made for individual applications, where some special property is required. Often, it is possible to sacrifice some general characteristic in order to obtain the special property. Compositions of this type include those of unusual water-resistance, special compositions for radio condensers, magneto insulation, and materials of marked opacity to X-rays for the manufacture of X-ray shields.

Transparent phenolic resins are available as plastics for molding and for casting. The cast resins are first formed into relatively simple shapes, cured by baking, and then machined to the desired form. The molding types can be handled in the conventional compression molds. The distinctive properties of these phenolic resins include hardness, heat resistance, dielectric strength, dimensional stability, and lightness in weight. Molded articles withstand temperatures up to 107° C. (225° F.) and even to 149° C. (300° F.) for short periods. Although they support combustion, they are relatively non-inflammable. They have a very high luster. One type of molding resin has a refractive index which approaches that of ruby. They are also extremely resistant to the action of ultra-violet light. Certain amber-colored resins are translucent to X-rays and are used as ports for X-ray machines. Some of the purest forms have the transparency of glass, which they surpass in strength and elasticity. They are odorless and tasteless, and water has no effect upon them.

Furfuryl-phenol plastics can be fabricated in a wide variety of ways, including both hot and cold molding. In cold molding, the plastic is formed by pressure at room temperature and cured subsequently by heat. These resins impart to finished articles properties which are similar to those of the ordinary phenol-formaldehyde binders, but in hot compression molding give a slower and more even rate of cure or set to the composition. This is an advantage with articles containing thick sections. These plastics are dark in color.

Urea-formaldehyde resins are the only light-colored thermosetting binders besides the transparent phenolic resins. Practically any color effect can be obtained with them. These compositions are widely used for pastel shades. Some of the resins are made by allowing both urea and thiourea to react with formaldehyde. Urea resins have very good mechanical and excellent electrical properties. They do not undergo surface carbonization in an electric arc as do phenolic plastics. They are unaffected by water if properly cured and have a high resistance to oils, solvents, and many chemicals. Weak alkalies and acids have no effect, but strong alkalies cause a slight deterioration. Strong acids produce decomposition. Urea plastics have a low burning rate, but shrink slightly under heat. The uncolored resins are unaffected by light. Severe exterior exposure to weather, however, causes a cracking of the surfaces. Cast urea resins have many of the properties of cast phenolic plastics.

Wood and paper pulp are generally used as fillers. The fibers of these materials are so small that, when impregnated with the binder, they can be used for obtaining translucent objects. Semi-translucent and opaque compositions are also manufactured. These different compositions are not so flexible as cellulose-derivative plastics, but are superior to these in many of their other properties. The compositions have unusual qualities of light diffusion when unpigmented and eliminate glare when used in thin sections. Moldings, used for indirect lighting fixtures, are superior to glass fixtures in being shatterproof. Another recent plastic application of these resins has been in production of crease-proof fabrics.

Cellulose plastics is the general term employed for plastics made from derivatives of cellulose, such as the cellulose esters, cellulose nitrate (miscalled nitrocellulose) and cellulose acetate, and the cellulose ethers, ethyl cellulose and benzyl cellulose. These are all true thermoplastic materials. They give molded articles of the greatest toughness and resilience of any of the plastics, and are extensively used for objects having thin-walled sections where other plastics may be too brittle. Nonvolatile plasticizers (organic solvents) or softening agents are generally incorporated to impart the desired working qualities. These plastics have excellent electrical properties. They are strong and show good wearing qualities. They can be machined, buffed, and cut. All types of color effects can be obtained with them, including such decorative effects as mother-of-pearl and tortoise shell.

The cellulose ethers are comparatively new. Hence, they have not been used so extensively as the older derivatives of cellulose, although they have some superior properties. Cellulose nitrate plastics (Celluloid) are very inflammable, but are much stronger than cellulose acetate plastics, and are less affected by water. Ethyl celluloses have the same tensile strength as cellulose nitrates, but much greater ductility. Benzyl cellulose also has good ductility. These newer plastics are also superior in electrical properties. Cellulose acetate and the ethers are relatively non-inflammable under ordinary conditions, but burn like wood when ignited. The cellulose plastics produce articles which are practically as clear as glass. Ethyl cellulose also shows nearly complete transmission to ultra-violet light between the wavelengths of 2800 and 4000 Angstrom units and is unaffected by sunlight. Cellulose nitrate which shows strong absorption below 2800 Angstrom units, and some absorption below 3300 Angstrom units, becomes embrittled and discolored upon exposure. Cellulose acetate which absorbs light below 2900 Angstrom units is only slightly affected. Benzyl cellulose has the disadvantages of cellulose nitrate in this respect. Strong acids decompose all the derivatives, but weak acids cause but slight deterioration. Ethyl cellulose resists both strong and weak alkalies. Weak alkalies have but a slight effect upon the others, but strong alkalies decompose them. They all show relatively high water absorptions but compare favorably with many of the other plastics containing fillers. Benzyl cellulose shows the least water absorption.

The *vinyl resins* all produce what might be called organic glasses. They include the colorless polymerides of methyl methacrylate, acrylates, styrene, vinyl chloride, vinyl acetate, and similar compounds. All these are perfectly odorless, tasteless, non-toxic, and transparent plastics. They are all thermoplastic, non-burning or slow burning, very tough, and chemically inert. They show practically no water absorption. Styrene and methyl methacrylate are the lightest of all organic binders. The shock resistance of the latter compares favorably with that of the phenolic resins. They transmit the ultra-violet wavelengths of light. Molded articles are distorted above temperatures of 60° to 85° C. (140° to 185° F.). The most significant property of the styrene resins is their low electrical power factors, which make them excellently suited for insulation to be used at radio frequencies. Vinyl chloride resins have a high resilience and are superior to rubber in flexing life and in resistance to deterioration. Copolymerides of vinyl chloride and acetate can be obtained both as filled and unfilled plastics.

Cumarone-indene resins soften over a narrow range of temperatures, which limits their use as plastic materials. They are very brittle, although they have excellent electrical properties which do not change with humidity. They are extensively used as binders in compositions for mastic floor tile, in the compounding of rubber, and in cold-molding compositions with other binders.

Rubber has only limited use as a plastic material unless it is vulcanized by combining it chemically with sulfur. Quick-curing hard rubber compositions are available which can be molded in much the same manner as resinous thermosetting plastics, which they resemble. Rubber compositions have the outstanding property of being able to undergo great deformation without becoming damaged structurally, but are not perfectly elastic according to the definition of elasticity given in Art. 3. When loads are applied and removed, a portion of the energy required to deform the rubber composition is lost in what is called "mechanical hysteresis." Owing to this property of high mechanical hysteresis, rubber compositions are utilized for absorbing shocks and reducing vibrations in machines. Deterioration of rubber tires and belting operated at high speed may be produced by heat generated by mechanical hysteresis. The mechanical, chemical, and electrical properties of hard rubber are excellent, but are impaired by exposure to sunlight and extensive contact with oil and other organic liquids. Metal inserts must be plated with some heat-resistant coating which does not react with sulfur.

Chlorinated and synthetic rubbers have been developed to replace natural rubber in order to overcome some of these handicaps. Chlorobutadiene rubbers show certain self-vulcanizing properties. They are unaffected by oils and gasoline. Polysulfide rubbers have good resistance to solvents in general. Polysulfide rubbers are cheap and can be molded or extruded with the usual plastic equipment, but an unpleasant odor limits them to certain types of applications. They are nevertheless extensively used for hose for gasoline, gaskets, printing rolls, and diaphragms.

Shellac is one of the oldest binders for molding compositions. It is still employed in large quantities for high-voltage electrical insulation where porcelain is the only extensively used competitive material. The shellac insulators are not so fragile as those made of porcelain and do not shatter. They have excellent characteristics to resist effects from arcing. The decomposition products formed under this condition are poor conductors of electricity, and surface carbonization is not excessive enough to cause serious danger of short circuits. The heat generated softens the lac, repairing any cracks which may be formed. Mixtures of shellac and phenolic resins are used for binders for insulation at intermediate voltages. These insulators have a greater resistance to heat than pure shellac compositions, which begin to deform at temperatures above 88° C. (190° F.). Shellac compositions are also used extensively for phonograph records, where scratch hardness and the tone qualities obtained are primary in importance. Shellac compositions remain thermoplastic at elevated temperatures for relatively long periods of time when compared with thermosetting resins. Prolonged heating, however, causes chemical changes to take place which improves the electrical and mechanical properties. Fabricated insulators made of laminated paper are cured, therefore, for periods as long as 10 hours at temperatures as high as 149° C. (300° F.).

Alkyd resins made from glycerin and phthalic anhydride have electrical properties similar to those of shellac, but are not used extensively as plastics except in thin films because of their slow rates of curing.

Natural resins other than shellac are used for blending with other binders. These compositions are applied almost entirely as filling compounds in the electrical industries. Asphalts, bitumens, pitches, and waxes have similar uses.

Casein plastics do not possess the degree of plasticity of resin binders, but are extensively used for articles which can be made in shallow molds. Compositions of milk casein of a wide variety of colors can be obtained at a relatively low price. Molding is accompanied by a considerable shrinkage, and curing is effected by treating the molded articles with formaldehyde solutions. Formaldehyde, however, can be incorporated with soya-bean casein prior to molding. This may greatly extend the use of this type of plastic.

Special compositions made from asphalt, drying oils, and asbestos are used for *cold molding.* Large tolerances must be allowed, depending upon the design and shape of the article, since shrinkage is from two to three times that for hot-molded plastics. Cold-molded articles are cured by baking. They do not have as good an appearance as articles made from other materials and consequently are usually used for parts hidden within an assembly. They are serviceable where resistance to heat and arcing are the primary needs.

636. Coloring Materials. Both organic and inorganic substances are used for coloring plastic compositions. The organic pigments and dyes are generally superior for this purpose since they are more resistant to acids and alkalies. Many of the binders, for example, destroy pigments such as the iron blues, chrome greens, umbers, and ochers. Permanence in color, however, cannot always be predicted in advance of trial. The white pigments are largely limited to the lithopones and titanium oxides.

These ingredients are commonly added during the incorporation of the binder with the filler. There are advantages, however, to precoloring the resins and to dyeing the fillers. Some resins are colored during their manufacture.

637. Preparation of the Compositions. Molding compositions containing fillers are manufactured by one of two general types of processes known as the wet and the dry methods. In the wet process the binder is first dissolved in a suitable solvent, usually alcohol, and incorporated with the fillers, plasticizers, and coloring matter in a closed dough mixer or kneader. The bulk of the solvent is then removed in a vacuum oven, and last traces eliminated by working the plastic composition between heated rolls. It is formed into sheets or broken into chips or a fine powder. In the dry process the ingredients are combined on heated mixing rolls. Urea resins are not isolated as such for plastic use, but the filler is added directly to the aqueous solutions containing the reaction product of urea and formaldehyde. The resulting coarse-grained, lumpy material is then spread upon trays, dried, and pulverized. Laminated plastics are made by coating the paper or fabric either with a spirit varnish of the binder or with molten resin. The coated paper is rolled into a tube, which may be split and flattened into sheets upon heating.

638. Molding. Articles are formed from plastic compositions by casting, by compression, by extrusion and injection molding, and by blowing. The simplest of these methods is *casting,* where melted resins are poured into the molds and then baked until they assume a permanent set.

Compression molding consists in placing a definite amount of the plastic in the bottom part of a heated mold, closing the mold, and then subjecting it to pressure in a hydraulic press. The mold is heated during the pressing operation. This causes the plastic material to soften and to flow, completely filling the cavity in the mold, which has the exact shape of the desired article. Thermosetting plastics are cured, and thermoplastic compositions are cooled, before the pressure is released. The temperatures and pressures employed vary according to the plastic to be molded. Temperatures range from 100° C. (212° F.) to 204° C. (400° F.) and pressures from 1000 to 6000 pounds per square inch, unless the material is capable of being cold molded at room temperature.

Injection molding consists in forcing softened plastic materials into a closed mold maintained at a temperature below the softening point of the composition. Pressures of 8000 pounds per square inch are satisfactory for many materials. This method is widely used for cellulose acetate compositions.

Extrusion molding is in many respects inverse of injection molding.

The softened plastic is forced from a chamber through a die or port in this process. Articles such as bars, rods, and tubes can be made in this manner.

Hollow molded objects are made by a special process known as *blowing*. Only certain plastics, for example, Celluloid and rubber, can be adapted to this process. Air or steam under pressure is used as the means for forcing two sheets of the plastic against the sides of a heated mold. Articles made from thermoplastics must be cooled before removal.

Four distinct types and a number of composite types of molds are made for these processes. They are generally constructed of steel which has been case-hardened before use, and are made in two or more sections. In compression molding, one part is forced into the other, causing the plastic to fill the cavity between the parts. The *flash type* of molds permit a slight excess (flash) of composition to escape during the final closure of the mold. *Positive types* permit no escape of material. They are used where the flash would lead to difficulties in obtaining the proper shape of the molded article. *Injection and blowing types* contain no movable parts. One of the largest items of expense in the manufacture of molded articles is the cost of molds, or dies, as they are called in the plant. Great savings can often be made in the construction of these molds and in subsequent operations by slight changes in design without affecting the usefulness or beauty of the molded articles. Engineers too frequently make the mistake of not submitting their drawings to experts on molding before having their designs finally approved.

639. Fields of Application. The properties of the different organic plastics fit them admirably for wide use in the aircraft industries. Molded and laminated parts have been used for a long time for control and navigation instruments and for electrical and radio equipment. The instrument board and radio room of a modern airliner are plastic exhibits in themselves. These materials are also widely used in the interior of airplanes for fittings and fixtures. Recent applications include molded plastic gasoline tanks, pipelines, direction-finder cases, and even the panes for curved windows. Figure 139 shows a plane equipped with cast acrylate-resin windows and turret and cockpit enclosures. Styrene rings are used for illuminating dashboard instruments for night flying. This method of lighting completely eliminates glare. New methods of construction include an entire fusilage molded in two parts from laminated phenolic plastics.

The newer models of automobiles feature also many applications of these materials. The banjo type of plastic steering wheel has proved to be an added safety feature during accidents. Shatter-proof glass windshields and windows are other examples of the use of plastics for this purpose, since the glass laminations are held together by organic plastics.

Dashboards, radio cabinets, trim, grill, window stops, sun-visors, and lighting fixtures are a few examples of the many other applications. Organic plastics are also extensively used for mechanical and electrical parts, including bearings, gears, and distributor heads. Red tail-lights have been made of cast phenolics. Rubber tires should not be overlooked in enumerating the uses of plastics. A recent English development eliminates glare from the headlights. The device consists of hexagonal tapered cones which are locked together to form a specially shaped lens. These units fit into the rim of existing headlamps, replacing the usual glass lens.

FIG. 139.—Airplane Equipped with Cast Acrylate-resin Windows and Turret and Cockpit Enclosures. (Courtesy of Röhm and Haas Co.)

Marine uses include many of those of the aircraft and automotive industries. In addition, certain applications are peculiar to this field, such as submarine battery jars, outboard motor parts, chimneys for hurricane-lamps, and collapsible boats.

Organic plastics have contributed greatly to the development of the electrical industries, especially in power transmission and in communication. Cheaper electricity still depends upon improvements in the insulating materials. Many of these insulators are made of organic plastics. Good mechanical strength is required in addition to electrical properties. The applications of organic plastics in these fields are too numerous to list here. It may suffice to point out that these materials are employed in the construction of such equipment as generators, motors, distributing apparatus, switchboards, panels, terminal boards, circuit breakers, electrical connections, magnetos, fuse-plugs, condensers, light-bulb bases, cartridge fuses, battery cases, transformers, and various housings for both operating equipment and measuring instruments. Telephones and many of their parts are also made of molded plastics. This particular equipment must be especially resistant to deterioration from perspiration. Some of the newer telephones for home use are now made in a wide variety of colors.

Fig. 140.—Livingroom Constructed of Laminated Plastics.

Architectural applications include another group of interesting uses. Figure 140 shows a livingroom of a home where laminated plastics have been used for the walls, ceiling, window sills, wainscoting, mantel, and fireplace. The high luster and fine finish of these will last for a very long period of time. The same type of construction was used in the powder room, lavatory, kitchen, and bathrooms of this house. The floor, lighting fixtures, lamps, and furniture might also have been made of these materials. Fabrics treated with organic plastics could have been used for the furniture coverings, shades, and curtains. This would prevent creasing and soiling, besides increasing their wearing properties. The book-ends, vases, flower pots, and china could be made of cast or molded materials. Cellophane, a thin-sheeted organic plastic, is used to protect lamp shades. Other applications of this type include door-knobs, latches, handles, toilet seats, bathroom fixtures, toilet flush valves, shower curtains, cabinets, correspondence files, kitchenware handles, refrigerator fronts, translucent Venetian blinds, and school desks. Even wider use of such applications is found in public buildings than in the home. The new Library of Congress Annex is a typical example of what can be accomplished with these substances. Metal finished with natural wood veneers using organic plastics as the adhesive gives the mellow effects of the older type of construction with the fireproof features of modern buildings.

Draftsmen's tools, miners' lamps, tool handles, printing type, bearings for lorries and cranes, grinding wheels, gears for power-driven shovels and mixers, special buckets for textile fibers, oil-well equipment, water-meters, X-ray tube guards, pipelines, tanks, towers, stills, pumps, conveyors, helmets, and goggles are a few scattered examples of industrial uses. Railroads employ these plastics for mechanical, electrical, and architectural applications. Laminated panels have solved locomotive-house corrosion problems.

Cast resins and Celluloid have given the engineer materials for the construction of models which he can use for studying the distribution of stresses under different actual loadings. This is done by placing the model in the path of polarized light and analyzing the colored interference figures produced by the internal strains.

QUESTIONS

1. Describe what is meant by an organic plastic, a binder, the resinoid state, a filler, a thermoplastic, a thermosetting resin, chemically setting compositions, addition polymerides, and condensation polymerides.
2. What are the important properties of organic plastics which contribute to their use as materials for construction?
3. Name the important groups of thermosetting plastics. What are some of their advantages and disadvantages?
4. Name the important groups of the thermoplastic materials. What are some of their advantages and disadvantages?
5. What are some of the different types of phenolic plastics? How do they differ?
6. Explain what is meant by a phenolic plastic, by a urea plastic, by a cellulose plastic, by an organic glass.
7. What types of substances are used as fillers and as coloring materials?
8. How are fillers incorporated with binders?

9. How are articles fabricated from organic plastics?

10. What are the different types of molds? How do they differ from one another?

11. What factors must be considered in designing a molded article?

12. List the possible items of cost in commercial molding.

13. Why is it desirable to submit drawings to a molding expert before having them approved?

14. What plastic composition or plastics would you select for manufacturing translucent Venetian blinds, for a pipeline to carry dilute sulfuric acid, for an electrical insulator to be placed near a boiler, for housing an X-ray tube, and for a float to be used in strong caustic solution? State your reasons.

15. What types of plastics would you expect to find being used in the airplane, automotive, and railroad industries?

16. How might a livingroom be finished with different plastic materials?

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