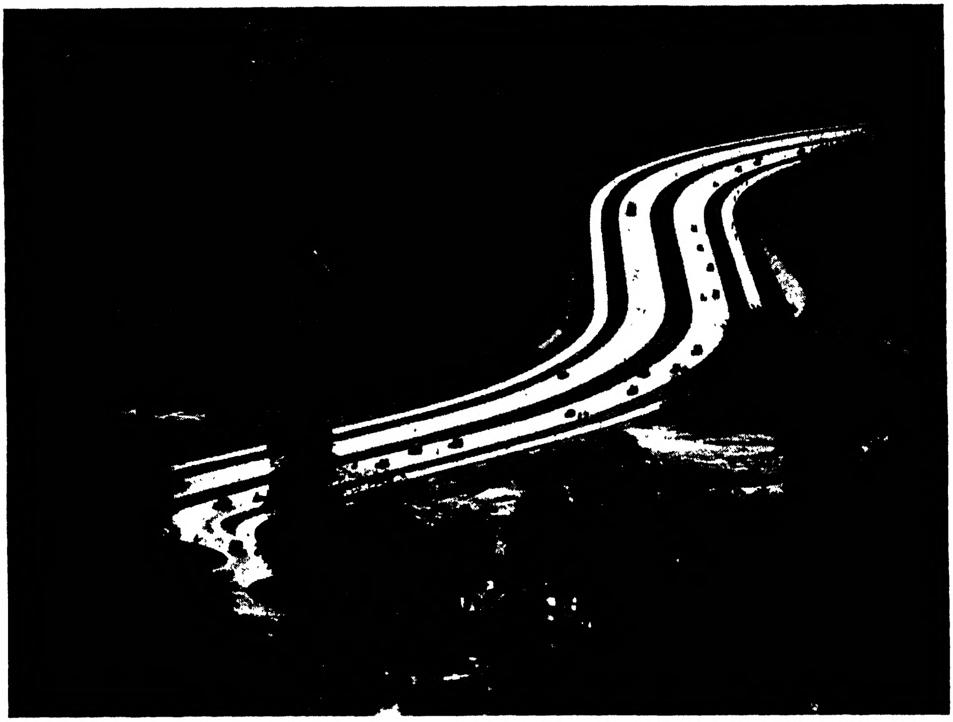

View of the Mickleham By-Pass Road from Box Hill.

This all-concrete road comprises dual carriageways 25 ft. wide and cycle tracks 9 ft. wide. It was built in 1937 to the design of Mr. W. P. Robinson, M.Inst.C.E., then County Surveyor of Surrey. The carriageways are 8 in. thick and the concrete was consolidated and finished by machine in strips 11 ft. to 12 ft wide. Transverse joints are formed at intervals of 90 ft., and in each of these bays there are two dummy joints at 30-ft. intervals.

DESIGN AND CONSTRUCTION OF CONCRETE ROADS

BY

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PREFACE

If we are to remain in the forefront of design and construction it is very necessary occasionally to examine the progress that has been made and the methods which have made that progress possible. As in all industries, the use of machinery in concrete road construction has developed at a tremendous pace, with the result that speed has been increased whilst high quality of the work has been maintained or surpassed. The student cannot hope to succeed if he starts where others have finished and fails to study the relation between design and construction and the progressive steps which have put him in a more fortunate position than his predecessors who had no previous experience to guide them.

This book, like the first edition, is meant to appeal to those who wish to practise or are practising as road engineers or contractors, rather than to examine the strictly theoretical side of concrete road engineering ; it is also hoped that it will be of interest to research workers in showing the use that has been made of their valuable work and indicating directions in which they could further develop our knowledge.

The authors express their thanks to Mr. A. Floyd, B.Sc., M.Inst.C.E., County Surveyor of West Sussex, Brigadier A. C. Hughes, B.Sc., M.Inst.C.E., County Surveyor of Hampshire, and Mr. W. P. Robinson, C.B.E., M.Inst.C.E., formerly County Surveyor of Surrey, for information supplied regarding concrete proportions and the grading of aggregates used in the construction of certain roads in their counties ; also to Messrs. John Mowlem & Co., Ltd., for information given in the chapter on Labour and Output.

R. A. B. S.
T. R. G.

January, 1946.

CONTENTS

CHAPTER I

SITING AND PLANNING

THE site and plan of a new road depend primarily on the volume and character of the traffic to be carried, and in many cases also on the topography of the land and its geological characteristics. For main roads the site and alignment are of first importance, whilst for estate roads where the area for development is generally comparatively limited and the traffic light, a plan most suited to the site and its surroundings should receive first consideration. The principles which govern these matters are the desirability of

(1) Avoiding long straight lengths—a gentle curve throughout avoids monotony and reduces headlight glare—and using very short straight lengths between curves.

(2) Avoiding areas such as marshes which present few natural drainage features.

(3) Reducing earthworks to a minimum.

(4) Selecting minimum curves and gradients.

(5) Providing ample space for margins, verges, reservations for trees and shrubs, underground mains and services, and future widening.

(6) Selecting sites for bridges, culverts, etc., and planning the new work so that it merges into its environment with the least possible disturbance of existing amenities.

Horizontal Curves.

The Ministry of Transport Memorandum on the Lay-out and Construction of Roads recommends a minimum radius of 1000 ft. wherever practicable. This is obviously unnecessary on secondary and estate roads; for such roads much sharper curves are quite practicable but, in general, the radius should not be less than 500 ft. It does not seem desirable to reduce the recommended radius on roads that may be subject to a speed limit, as the present limit of 30 miles an hour on such roads is an expedient that may not always be desirable.

Vertical Curves.

Vertical curves are necessary at all points where a change of gradient occurs. At summits, vertical curves are required to ease the path of the vehicle and to provide adequate visibility. The Ministry of Transport recommends that "an endeavour should be made to secure that from any point on either approach a driver may have a clear view of any vehicle proceeding from the opposite direction when such vehicle is not less than 500 ft. from him, assuming the eye level to be 3 ft. 9 in. above the carriageway." To comply with this requirement a vertical parabolic transition curve over a summit must conform to the expression

$$d_c = 5(G_1 + G_2) - 3{\cdot}75,$$

where G_1 and G_2 are the gradients of the approach slopes expressed as percentages and d_c is the vertical distance in feet of the summit of the road curve below the point of intersection of the two projected slopes.

Horizontal Sight Distance.

The Ministry of Transport recommends the same visibility on horizontal as on vertical curves, namely, 500 ft. There is no close agreement between highway engineers on the limits of safe sight distance. The continual increase in density and speed of traffic, and divergence of opinion on the relative importance of " reasonable speed " and cost, make it difficult to apply hard-and-fast rules.

The safe sight distance is dependent on the braking power of the vehicle, and is generally taken as being equal to twice the distance required for a vehicle to be brought to a stop. The coefficient of friction between the tyres and the road surface plays an important part in the determination of this distance, and varies according to the nature and condition of the road surface and of the tyres. American practice usually requires from 350 ft. to 500 ft. as the minimum sight distance between any two points 5 ft. above the road surface, for both horizontal and vertical curves.

If S ft. are required by a vehicle of weight W to come to rest from a velocity of V_1 ft. per second when the coefficient of friction is f, then by the Principle of Work

$$f \times S \times W = \frac{WV_1^2}{2g}, \text{ or } S = \frac{V_1^2}{2gf}.$$

If the velocity is V miles per hour, then $S = \dfrac{V^2}{29 \cdot 4f}$.

Allowing half a second for the reaction time of the driver, this becomes

$$S = \frac{V^2}{29 \cdot 4f} + 0 \cdot 73V.$$

This formula is used in Oregon, U.S.A., in the approximate form

$$S = \frac{V^2}{30f} + 0 \cdot 73V.$$

For example, if $V = 50$ miles per hour and f for wet concrete $= 0 \cdot 5$, the clear sight distance required is $S = 203$ ft. and the safe sight distance is 406 ft. when traffic proceeds in both directions.

Effective Width.

The " effective width " of a roadway has been defined as the width required to accommodate the road and all the separate units which comprise the road, such as cuttings, embankments, verges, ditches and margins. Generally the effective width is the width between fences which in the case of private streets, estate roads, etc., is fixed by by-laws. In ordinary circumstances the minimum effective width of the highway required to accommodate the proposed plan is given by the Ministry of Transport as follows.

	Minimum effective width (in ft.)
(1) Single carriageways not exceeding 30 ft. with footpaths	60
(2) Single carriageways not exceeding 30 ft. with footpaths and cycle tracks	80
(3) Dual carriageways (each for two lines of traffic) with footpaths and no cycle tracks	80
(4) Dual carriageways (each for two lines of traffic) with footpaths and cycle tracks	100
(5) Dual carriageways (each for three lines of traffic) with footpaths but no cycle tracks	100
(6) Dual carriageways (each for three lines of traffic) with footpaths and cycle tracks	120

Roads which are likely to be used by a large number of heavy vehicles will require a distance of 70 ft. between the outer kerbs of dual carriageways to provide adequate turning space. In such cases the width in (3) should be increased to 100 ft., and those in (4) to 120 ft.

Carriageways.

The width for a line of traffic should not be less than 10 ft., and the divisions between them clearly marked. The longitudinal joints of a concrete road may with advantage be arranged to indicate traffic lines. With the possibility of the allowable overall width of vehicles being increased to 8 ft., it would not be unwise to make 11 ft. the minimum width for each line of traffic. In the case of unclassified roads and one-way link roads, the width of the carriageway should not be less than 16 ft.

Longitudinal Section.

This will be determined by:

(1) THE CONTOUR OF THE GROUND.—In normal circumstances, the Ministry of Transport recommends a gradient of 1 in 30 as the maximum, but in hilly districts steeper gradients may be necessary. A gradient of 1 in 15 for well-finished concrete surfaces has proved satisfactory, and this may be further increased to 1 in 10 or even less provided the surface is suitably treated, as described later. Steep gradients, however, should be avoided wherever possible, particularly at bridge approaches, road junctions, and curves of small radius.

(2) DRAINAGE.—In order to facilitate surface-water drainage the Ministry of Transport recommends a minimum gradient for the carriageway channels of 1 in 250. Flatter gradients are frequently adopted for concrete roads by reason of the true surface finish that this construction renders possible.

(3) LEVEL OF ADJOINING PROPERTY.—Land chosen for building development, particularly in the case of estate roads, is generally fairly level. In such cases the crown of the road should be not less than 9 in. below that of the surrounding ground, thus leaving the garden top soil undisturbed and allowing sufficient depth for kerbs and footpaths and for the kerbs to the centre strips in dual carriage ways.

Constants of Design.

The constants of design adopted for the German motor roads are:

	Type of country		
	Lowland	Hilly	Mountainous
Speed (miles per hour)	100	90	80
Maximum gradient (per cent.)	4	6	8
Radius of horizontal curves in feet	5,906–6,562	2,625–3,281	1,967
Minimum radius of vertical curves in feet.			
Summit	54,793	29,529	16,410
Depression	16,410	9,843	9,843
Range of visibility in feet	918	810	525
Normal crossfall without camber	1 in 66	—	—

Camber.

The only purpose in cambering a road surface is to provide a watershed for rainwater, and the camber should therefore be the minimum for this purpose. For kerbed carriageways, private streets, estate roads, etc., the usual crossfall is about 1 in 48. If surface water is allowed to drain on to the verges, a crossfall of 1 in 66 falling without camber to the outer margin is generally satisfactory and provides an ample cleansing gradient for stormwater. This only applies to dual carriageways—the quicker the water runs off the less the inconvenience caused by the splashing of windscreens.

CHAPTER II

EXCAVATION AND PREPARATION OF THE FOUNDATION

Soils are variable in their behaviour, and it is most important that the properties of the soil should be taken into account when considering the foundation on which a road is to be built. Some soils shrink and crack when they dry, and swell when moisture is taken up; others absorb large quantities of moisture by capillarity from lower-lying strata; whilst others retain a uniformly low moisture content, are very stable, and change only slightly in volume, thus being little affected in regard to their load-carrying capacity.

The properties primarily responsible for the inability of soil to carry a required load are (1) change of volume with change in moisture content (clay); (2) absorbent capacity inducing capillary action (chalky soils, sandy loams, etc.); (3) "sponginess," or recovery on removal of load (peat and alluvial deposits generally); (4) erosion or disintegration in presence of water (peaty soils, loam, etc.); and (5) lack of internal cohesion (peat and loam).

The characteristics of soils vary from one extreme to the other, and the question arises of the dividing line between good and bad soils and how may the engineer best take account of these variable characteristics in the design of roads.

It is very important that the foundation shall have uniform density. It is, perhaps, not so necessary that the foundation be consolidated to a great density as that the density—whatever it may be—shall be uniform throughout, and every effort should be made in order that this may be secured. To neglect this precaution is to incur the risk of unequal settlement, the formation of hollow spots and depressions in the road surface, and finally the general disintegration of the surfacing material.

Soil Survey.

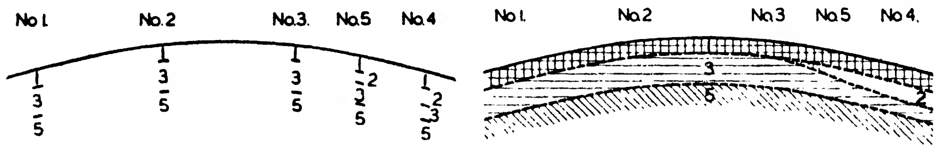
Considerable attention is now given to the study of the behaviour of various types of soil, and it is possible to decide which soils are likely to provide a sound foundation and what treatment should be given to other classes of soil in order that they may provide adequate stability for the surfacing material. Preliminary investigations should include a soil survey which will indicate the nature of the ground by the aid of borings, the results being plotted to form a soil profile. The steps in preparing a soil profile may be briefly outlined as follows.

Borings with a post-hole auger are carried down to at least 3 ft. below formation level at intervals of about 300 ft. along the centre-line of the road, and the depths and characteristics of the various layers of soil are determined and recorded, each distinctive layer being identified by a number.

Fig. 1 shows the details of a soil profile, alternate numbers being used for successive soil layers so as to allow the inclusion of other layers that may be encountered in later sections. In the assumed case, the same three layers Nos. 1, 3, and 5 occur at each bore. However, at bore No. 4 there is a new soil type (2) between soils 1 and 3. In order to find the end of soil 2, one or more bores between Nos. 3 and 4 must be examined. Thus, No. 5 is selected. The complete profile is shown in *Fig. 2*.

This work is estimated to cost from £30 to £50 per mile. Although the cost is low it is not necessary to carry out soil surveys for small schemes such as housing estates and private streets unless these include thoroughfares on newly filled ground which may have to carry heavy traffic in the future. In such cases a soil survey may be the means of preventing differential slab movement, cracking, corner breaks, etc., which are difficult to repair and add greatly to maintenance costs.

Concrete, whether as a foundation in place of hardcore or pitching or used as a running surface, has eliminated much of the labour and expense in the preparation of the foundation. By virtue of its monolithic character and, in the large majority of cases, aided by the introduction of reinforcement, concrete



Figs. 1 and 2.—Soil Profile Diagrams.

is superior to other materials in distributing the live load over the foundation, since weak spots (provided they are not too numerous or of too great a span) are " bridged " by the superimposed concrete slab which, acting as a raft foundation, must be sufficiently strong for the weight of traffic it has to carry. In forming a bed for a concrete carriageway, the features that should receive primary consideration are (1) drainage, (2) consolidation, and (3) uniformity of level and section.

The problem of drainage includes not only the disposal of surface water from the carriageway but also the collection and disposal of both surface and subsoil water flowing towards the carriageway from the verges and surrounding ground. The drainage of surface water from adjoining ground may involve the provision of culverts, diversion of streams, and other measures beyond the scope of this work, and attention is therefore given here to the subject only so far as it relates to the construction of the carriageway.

Drainage of the Subsoil.

Since the physical properties of soils vary with their moisture content their drainage is of primary importance, as the presence of excessive or varying water content in the soil leads to insufficient or variable support. Open or granular soils present no difficulty regarding drainage. The chief problem arises in connection with the treatment of fine-grained soils since they retain moisture and also accumulate moisture by capillary attraction. The main object, therefore, is to maintain the ground under and adjacent to the carriageway in as uniform a condition as possible by preventing moisture entering the road bed rather than by draining all water from it. The percolation of moisture through soil pores may take place due to gravity or to capillary attraction depending upon the nature of the soil. In soils of an open texture on which sand or gravel predominates the percolation of moisture is almost entirely due to gravity and can easily be collected and removed by properly spaced drains. Soils which are less permeable, such as sandy clay, receive their moisture from the underlying water table by capillary action as well as from the percolation of surface water. In either case the passage of moisture can be intercepted and its movement controlled by the provision of suitable drainage arrangements.

An exception is fine sand which has been noticed to have a capillary rise of as much as 8 ft., whilst in clays and sandy loams a rise of 3 ft. or 4 ft. is not uncommon.

Water cannot easily be drained from heavy clays because it is held in suspension by capillary forces. It is questionable, therefore, whether the provision of subsoil drains under the carriageway, particularly in stiff clayey ground, removes much water by gravity. However, even in such soils the height to which water rises by capillary attraction is largely governed by the height to which the water table rises, and sub-drains may be useful in lowering that level provided they are laid at a suitable depth and can discharge freely. Moreover, water will rise higher by capillary action in a wet soil than in one that is dry, and since drains keep the soil drier the effect of capillarity is decreased. Although few soils become excessively soft by the presence of moisture through capillary action alone, the amount may be such that the addition of only a very small quantity of free water will cause softening. In most cases this can be prevented by providing a ditch on each side of the road to drain the moisture held in a permeable soil more or less equally for the full width of the carriageway. These ditches, provided they are of sufficient depth, will prevent the water table rising above their invert level and will thus ensure that capillary moisture does not reach the soil immediately under the carriageway. This is particularly essential for permeable soils, such as silts and silty clays, which possess high capillary properties; for such material shallow ditches are useless and only comparatively deep lateral ditches will be efficient.

Action of Pipe Drains.—Subsoil pipes, or tiles as they are commonly termed, when laid in or above an impervious stratum provide artificial channels into which excess water can enter and be carried away. The water enters the drain through the open joints between the pipes and not through the barrel unless the latter is made of very open textured concrete such as that shown in *Fig.* 3. Assuming that after rainfall the subsoil to a certain depth becomes saturated and that there are subsoil drains within the saturated area, the movement of the water from the surface to the drain is as follows. The water in the soil at the level of the drain is under pressure due to the head of water in the soil above. This pressure causes the water in the soil around the drain to enter the joints since this is the path of least resistance, and the relief thus afforded starts a flow of water in the direction of the drain (*Fig.* 4). As the level of the ground water is lowered its surface does not remain horizontal but becomes undulating, the lowest points being those over the pipes and the summits about mid-way between them. This is because the water over the drain has a shorter distance to travel to reach the pipes, thus causing the formation of a vortex. As the water in the soil above the drain is slowly removed, the water table becomes more undulating until the position in curve 4 is reached. From this stage the slope of the water table becomes flatter, as shown by curves 5 and 6, until the pressure tending to cause flow is just balanced by the resistance to flow offered by the soil particles and a stage of equilibrium is reached as shown by curve 6.

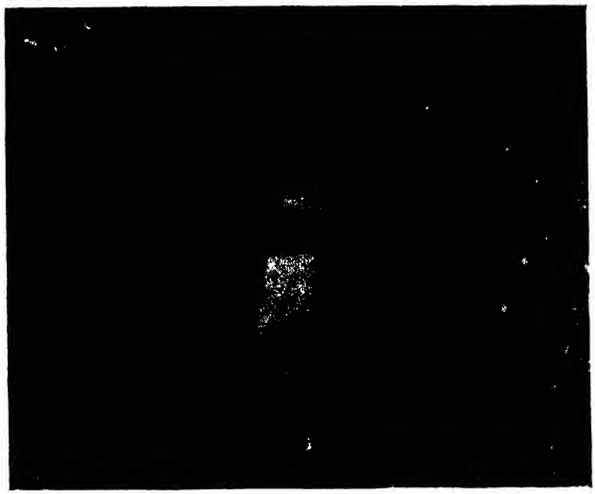


FIG. 3.—POROUS CONCRETE DRAINAGE PIPES.

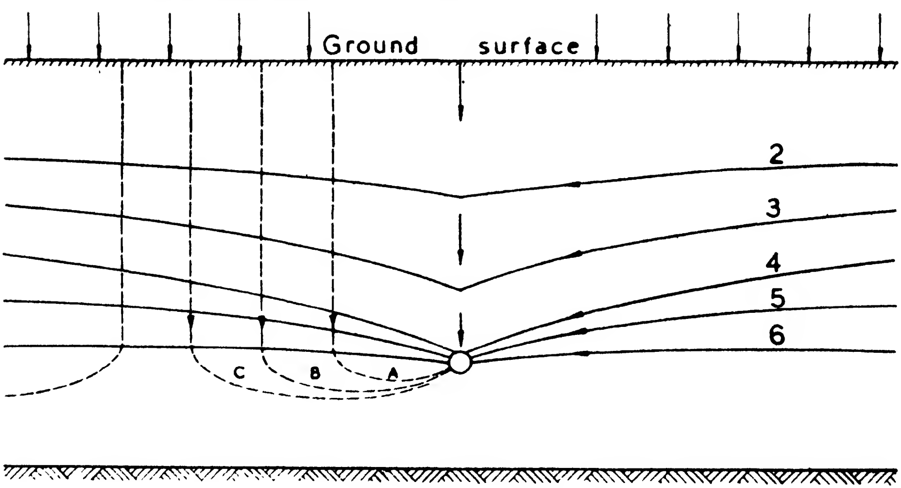


FIG. 4.—MOVEMENT OF WATER NEAR DRAIN.

The water in the soil above the drain moves directly downward, or as nearly as the irregular passages in the soil will permit, and enters the top of the pipe joint; other water enters at the bottom and sides of the joint because of the pressure of the water above curves A, B, and C.

Position of Drains.—The most efficient position for drains, provided the depth is not excessive, is as close as possible to the impervious stratum. Soils which have a high degree of capillarity require drains to be placed at a lower depth than in porous soils, at least 6 ft. being necessary. There is no hard and fast rule that can be followed to determine the depth at which drains should be laid, and each case must be considered separately. The main object is to ensure that the water table does not rise to a height which will allow capillary action to take place in the soil on which the concrete paving is laid. For example, suppose the subsoil consists of a mixture of clay and granular material, such as sand, the clay content being about 60 per cent. In such a case drains should be provided, particularly if an examination shows that the water table is likely

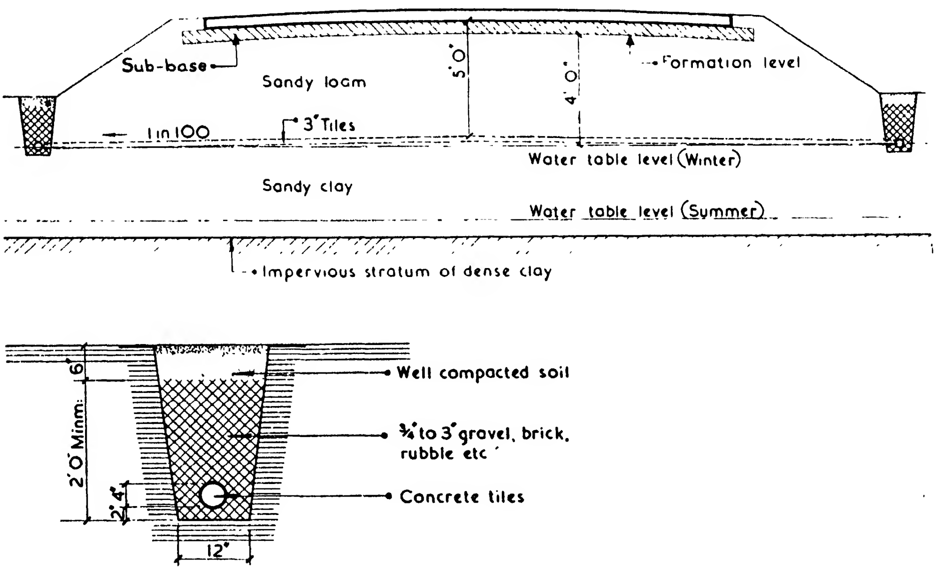


Fig. 5.—Typical Drainage Detail.

to rise to within 3 ft. or 4 ft. of the sub-base ; in this case 3-in. tile drains should be provided at from 40 ft. to 45 ft. intervals and at a depth of 3 to 4 ft.

The easiest material to drain is granular soil, such as coarse sand and gravel, as water moves through this easily by gravity and its stability is rarely affected by normal changes in water content. Fine sand, however, tends to retain its moisture content and, in certain circumstances, may become inundated and form a stratum of running sand.

Fig. 5 illustrates a suitable position for drains for a soil such as sandy loam overlying a stratum of sandy clay below which is an impervious stratum of yellow clay, assuming that borings reveal that the water table is 4 ft. below formation level in winter and 8 ft. in summer. Since capillary water may rise 3 ft. to 4 ft. in sandy loam, the water table must be lowered at least 12 in. to prevent capillary water reaching the road bed. A suitable drainage would be 3-in. pipes at a depth of 5 ft. from formation level and spaced about 200 ft. apart. The drain should have sufficient fall to the side drains, say 1 in 100, to ensure rapid discharge of all subsoil water collected. These side drains will also help materially to lower the water table, and in many cases may alone be sufficient drainage. If the fall of the ground is in a transverse direction to that of the roadway, then the provision of longitudinal drains should be considered.

SPACING OF DRAINS.—The spacing of drains is determined by the longitudinal slope of the ground, the nature of the soil, and the depth of the drain below formation level. *Table* I may be used for general guidance for subsoil drains of 3-in. bore and for the types of soil mentioned.

TABLE I.—SPACING OF DRAINS.

	Depth to invert	
	2 ft. to 3 ft.	3 ft. to 4 ft.
Sand	100–150 ft.	150–300 ft.
Sandy loam . . .	85–100 ft.	100–150 ft.
Loam	75– 85 ft.	85–100 ft.
Clay loam	45– 55 ft.	55– 65 ft.
Sandy clay. . . .	35– 40 ft.	40– 45 ft.
Clay	25– 30 ft.	30– 35 ft.

CONSTRUCTION OF DRAINS.—Drains should be not less than 18 in. below the formation, the depth being increased to at least 24 in. for silty soils in wet localities. The diameter of the pipe cannot be fixed by calculation, as it is rarely possible to estimate the amount of water a drain will be required to carry. General practice is to use pipes not less than 3 in. and not more than 4 in. in diameter, except where the point of discharge exceeds 100 yd., where the ground is waterlogged, or where the fall is less than 1 in 200. The width of the outfall trench in which the side drains are laid should be at least 3 in. greater than the external diameter of the pipe, and the filling should consist of dry material such as clinker, gravel, quarry waste, or similar material from which particles less than ¾ in. gauge have been screened and which can be properly packed between the pipeline and the sides of the trench. A suitable grading is 3 in. to ¾ in. The pipes should be of porous concrete because these are not only strong with a high degree of porosity but, having shallow spigots and sockets, they are not easily displaced when the trench is being filled.

OUTFALLS.—The drains should be connected every 250 ft. to 300 ft. either to side ditches or to the surface-water drainage system, suitable catchpits or inspection chambers being provided to avoid accumulations of silt, leaves, etc.

Surface Water Drainage.

For urban districts, built-up areas, and some arterial roads the carriageway must be given sufficient slope or camber to ensure that rainwater is conducted as quickly as possible to the channels and thence to gullies or outlets connected to the piped system. In rural and other districts where no piped system is available the surface water must be discharged either directly on to sloping verges or through grips cut through these verges which lead to open ditches running parallel with the road. The former method has proved most efficient, and has the additional advantage that in an emergency an uninterrupted run-off for a vehicle is always available.

GULLIES, OUTLETS, ETC.—The spacing of outlets for the discharge of surface water cannot easily be determined with precision, as it is influenced by the width, gradient, and camber of the carriageway and the texture of the concrete surface, as well as by the type of outlet such as an ordinary gulley or kerb outlet. Other factors, such as road junctions and their gradients, locality, and general situation must also be considered, for example, more gullies will be required in built-up areas where grit and other refuse are liable to collect than for roads in open country. A sufficient number of gullies will also facilitate the rapid discharge of stormwater and so prevent flooding.

The minimum longitudinal gradient for concrete is about 1 in 400, with gullies spaced at 100-ft. intervals. With gradients of about 1 in 100 it may be accepted that, for a 20-ft. carriageway and a normal camber of 1 in 48, gullies should be spaced about 180 ft. apart, whilst a 30-ft. carriageway and the same camber will require a spacing of 120 ft.

For gradients of 1 in 15 and under the spacing should be further reduced to possibly 100 ft. or less to prevent water rushing over the gulley grating; alternatively, double outlets may be provided. The spacing shown in *Table* II may be taken as an approximate guide to maximum spacing.

TABLE II.

Longitudinal gradient	Spacing in ft. for camber of		
	1 in 36	1 in 48	1 in 60
1 in 10	200 (2 outlets)	150 (2 outlets)	120 (2 outlets)
1 in 30	300	250	180
1 in 300. . . .	250	200	150

Because kerb outlets are normally of smaller capacity than channel gullies and their "lead-in" less direct, their spacing should be reduced by 15 to 20 per cent. for gradients of 1 in 30 to 1 in 300.

The Ministry of Transport recommends that gullies should be placed in the verge at the back of the kerb with side entrance gratings. From the point of view of traffic this is undoubtedly the best position and is generally adopted for country roads. In urban areas, where footpaths abut the carriageway, pedestrians as well as vehicles must be considered, and in this case the channel type of outlet is more suitable.

Compaction of the Foundation.

The compaction of a cohesive soil at optimum moisture content results in a material that is slow to absorb moisture and one that has greater mechanical strength because of its increased density. By adequately compacting the soil it is possible to construct earth embankments equal in density to that attained after years of settlement and use, and to provide a sub-base in cuttings that will greatly increase its traffic-carrying capacity. The extent to which the process of compaction can usefully be undertaken has not been fully determined.

American practice requires that for major roadwork the top 8 in. or so of the foundation should be compacted to give 90 per cent. to 95 per cent. of its maximum density. A very heavy roller is not essential, a machine of 6 to 10 tons weight being generally sufficient for most soils. Tandem smooth rollers are more efficient than the older type of three-wheeler, since their greater mobility compensates for their lighter weight.

Experience indicates that for the compaction of embankments, fills, stabilised soil, etc., sheepsfoot rollers give a high degree of compaction. Smooth rollers of about 8 tons weight generally require fewer passes than sheepsfoot rollers for equal compaction, but this again depends upon the type of soil; for example, a sheepsfoot roller will give better results on brick earth whilst an 8-ton smooth roller is superior on hoggin. For efficient compaction the area of the tamping feet and the unit pressures necessary for various soils must be considered. The following are commonly adopted for sandy soils: Unit pressures, 50 to 100 lb. per square inch; tamping feet, 10 to 12 sq. in. Sandy loams and light clay loams: Unit pressures, 100 to 200 lb. per square inch; tamping feet, about 7 sq. in. Heavy clays and soils containing an appreciable amount of coarse material over $\frac{3}{16}$-in. gauge: Unit pressures, 200 to 400 lb. per square inch; tamping feet, 5 to 6 sq. in. The foundation should be carefully examined during rolling, and all spongy parts removed and made good with suitable material until a uniform degree of consolidation is obtained. Sheepsfoot rollers are not effective for compacting clean sand, gravel, broken stone and similar granular material without the addition of clay or other binder. They should not be used on wet, heavy clays.

Sub-Base.

It is now almost common practice to provide an insulating medium, or sub-base, between the underside of the concrete raft and the foundation. The purpose of the sub-base is to (1) Spread traffic loads over a larger area of the foundation; (2) Act as a blanket or insulating medium protecting the formation from frost action. (3) Provide a firm, dry, and accurately shaped foundation on which to lay the concrete. (4) Ensure that a base of uniform bearing capacity is obtained by consolidation by rolling, so that weak or soft areas are revealed. (5) Prevent seepage of liquid cement and reduce the friction between the slab and the sub-base when the latter is covered with waterproof paper.

MATERIALS.—Sub-base materials may consist of any hard granular material that is reasonably well graded so that when it is "blinded" and consolidated by a roller a dense even surface is obtained. For private streets and estate roads a 3-ton to 5-ton roller is generally sufficient, but for roads to carry heavy traffic an 8-ton to 10-ton roller is recommended.

Well-burned clinker, gravel, crushed brick, blast furnace slag, and sand, are the materials most commonly used. If clinker from a destructor is used it is important that the concrete raft should be constructed on it within a reasonable period of its being laid and while it is still in a dry state. Cases have occurred where heavy rain, coupled with a clay or badly-drained foundation, has caused water to accumulate and saturate the clinker formation and, due to the lack of time for this water to disperse, impurities have been absorbed from the clinker and acted injuriously on the underside of the concrete slab. An additional treatment which may go far to remedy such a condition, and which has additional advantages, is to spread waterproof paper or bituminised jute immediately above the clinker or ash formation a few minutes before the slab is laid. This prevents absorption of liquid cement by the clinker, as invariably happens if a wet mix of concrete is used. It also prevents intermingling of the concrete and clinker caused by tamping. Cores taken from concrete road slabs show that in the majority of cases the bottom 1 in. to 1½ in. rarely approaches the density of the upper portions, and in many instances is valueless as concrete or as protection to reinforcement, unless a waterproof sheeting has been laid over the formation.

THICKNESS.—The selection of a suitable depth for the sub-base should be decided with regard to (*a*) the contour of the ground, (*b*) the degree of exposure of the foundation to atmospheric conditions, (*c*) the nature of the foundation, (*d*) the slab thickness, and (*e*) the weight and volume of the traffic for which the road is intended. The relationship between these factors still remains to be determined; *Table* III, however, gives dimensions based upon current practice and experience.

TABLE III.—THICKNESS OF SUB-BASE FOR VARIOUS SOILS AND LOADS.

Type of soil	Consolidated thickness of sub-base		
	Light traffic	Medium traffic	Heavy traffic
Loam; silty soil with fine sand and clay	3 in.	6 in. to 9 in., compacted in two layers	9 in to 12 in., compacted in two layers
Clay soils and well-consolidated embankments	2 in.	3 in. to 4 in.	4 in. to 6 in.
Gravel; chalk; rock; well-graded sandy soils.	1 in.	2 in.	2 in.

Light traffic may be taken as that normally using estate roads, private streets, and rural thoroughfares.

Medium traffic is that using Class B country roads and the less important Class A roads.

Heavy traffic is that using Class A roads, city streets, and busy thoroughfares.

Excavation.

The rapid increase in the use of concrete for roads, aerodromes, and similar paving has been followed by equally rapid progress in the application of machines to prepare the ground on which the paving is to be laid so that constructional work can be carried out in a more or less continuous sequence of operations. Machines are now available for the removal of every type of soil. The types of machines commonly used for excavation may be divided into two main classes, namely, (*a*) Machines which operate whilst stationary, e.g. the mechanical excavator or digger; and (*b*) Machines which work while moving on their own track, e.g. the bulldozer. The type of plant to be used does not depend entirely on the volume of material to be excavated, but is also governed by the height of any embankments and the depth of any cuttings involved. In addition, the volume of material to be removed is important, since haulage may prove expensive unless suitable plant is employed.

Plant.

MECHANICAL EXCAVATORS.—This equipment may take the form of a face shovel, drag shovel, skimmer dragline, grab, or crane. Excavators are generally mounted on crawler tracks and move under their own power. Petrol and Diesel types, developing about 45 b.h.p., are the most common, the fuel consumption for a ½-cu. yd. machine being about 2 gallons per hour. Excavator buckets are made in sizes from ¼ cu. yd. to 3 cu. yd. capacity, those normally used for road work being ⅜ cu. yd. to ½ cu. yd. for shallow cuts up to 10 ft. in depth, ¾ cu. yd. to 1 cu. yd. for cuts deeper than 10 ft., and 1½ cu. yd. to 2 cu. yd. for deep cuttings. The output depends upon the nature of the soil. For general guidance, it may be said that an output of approximately 80 cu. yd. per hour may be attained with a 1-cu.-yd. bucket working in ordinary soil and light clay. Outputs proportional to the bucket sizes are usually attained, e.g. a ⅜-cu.-yd. bucket removes approximately 30 cu. yd. per hour and a 2-cu.-yd. bucket 160 cu. yd. per hour.

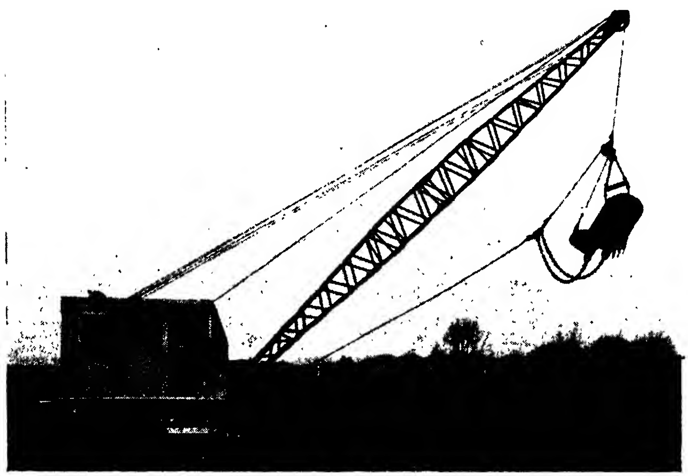


FIG. 6.—DRAGLINE EXCAVATOR.

DRAGLINE EXCAVATOR.—*Fig.* 6 shows a popular type of single-bucket excavator which has now largely replaced the power shovel for the reason that it normally stands on the surface of the excavation and digs below its own level for depths up to 16 ft. or more. A further advantage is that wider digging and discharging ranges may be obtained, due to the long booms with which the machines are fitted. The bucket sizes vary from ¼ cu. yd. to 20 cu. yd., whilst booms up to 250 ft. in length are sometimes used. This machine is particularly useful for forming banks from borrow-pits.

For embankments up to 5 ft. in height, dragline excavators having a boom of about 25 ft., together with a blade grader, can be usefully employed if soil can be removed from lateral borrow-pits. In such cases the excavator should work from the centre-line of the road, digging on each side and moving backwards.

For embankments from 5 ft. to 10 ft. in height the excavator can best operate from a berm at the toe of the embankment, the bottom half of the bank being filled from one side and the top half from the other.

Fig. 7.—Skimmer for Shallow Cuts.

Skimmer.—This machine (*Fig.* 7) is a small single-bucket excavator with a long and more or less horizontal scraping action, and is chiefly used for cuts not exceeding 6 ft. in height. One of its advantages is that it leaves a comparatively level surface.

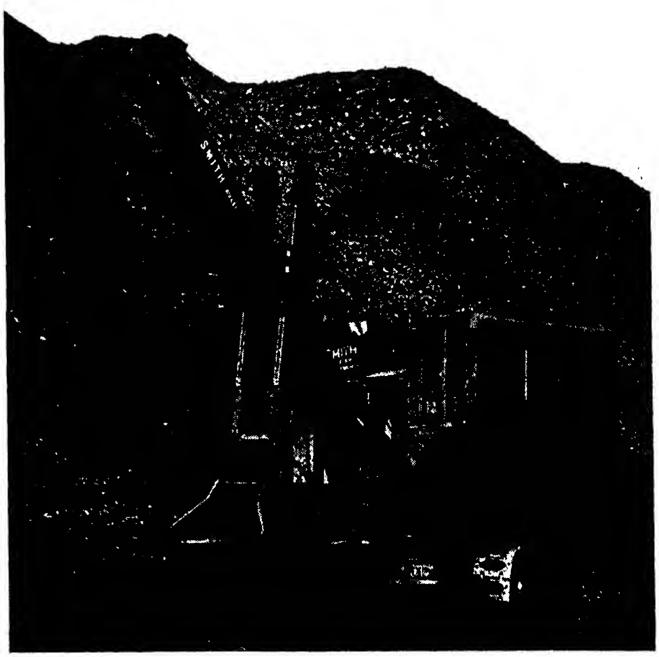


Fig. 8.—Shovel for Heavy Material and Rock.

FACE SHOVEL.—This type of excavator (*Fig.* 8) is used for the removal of rock, chalk, and similar quarried material. It requires a face against which to work, usually 8 ft. to 10 ft. high for the larger machines and 4 ft. to 6 ft. high for the smaller. Owing to its robust construction it will dig heavy material, such as boulder clay and soft disintegrated rock, without the assistance of explosives. It is obtainable in many sizes ranging from ¼ cu. yd. to 3 cu. yd. capacity.

GRAB OR CLAMSHELL.—This machine (*Fig.* 9) is sometimes employed for the removal of surplus excavated material and the rehandling of loose material. It can also be mounted on a barge for dredging purposes. It is frequently used

FIG. 9.—GRAB FOR HANDLING LOOSE MATERIAL.

for removing aggregates from stock piles to lorries or to the hoppers of a batching plant.

CRAWLER-TRACK MACHINES.

Machines in this category are fitted with self-laying tracks of the crawler type, and are available in a number of designs. The following notes and illustrations are confined to machines of this class commonly used for earth-moving in connection with road works.

BLADE GRADER.—These machines are mostly used for levelling the ground or preparing the formation, for making wide channels for drainage along the roadside, and for trimming the sides of cuttings and embankments. The usual type consists of an angled blade 8 ft. to 12 ft. long, supported on a framework mounted on wheels with means for tilting, swivelling, elevating and lowering the blade, and also for inclining the wheels relative to the axles. In the larger models all movements of the blade are controlled hydraulically by means of a small engine and pump mounted on the grader.

AUTO-PATROL OR MOTOR GRADER.—This machine (*Fig.* 10) is generally fitted with pneumatic tyres and driven by a 35-h.p. motor. It may be used for several purposes by means of appropriate attachments, such as scraper blade, scarifier,

FIG. 10.—GRADER FOR SCARIFYING AND SHAPING.

etc. The principal uses are shaping the formation for roadwork, scarifying and loosening soil to a uniform depth, and forming windrows.

ELEVATING GRADER.—It is claimed that this machine (*Fig.* 11) is the most economical equipment so far invented for digging earth and removing it to one side. It consists of a disc plough which ploughs a ribbon of earth on to a conveyor belt, from 18 ft. to 24 ft. long and 42 in. to 48 in. wide, which delivers the

FIG. 11.—ELEVATING GRADER LOADING INTO TRAILER WAGONS.

soil either in a continuous heap parallel to the cut or into lorries or other vehicles. Under favourable conditions up to 400 cu. yd. (solid) per hour can be removed. It is made in two sizes for operation with a 78-h.p. or 110-h.p. tractor.

BULLDOZERS and ANGLEDOZERS.—These machines (*Figs.* 12 and 13) are similar in principle, the only difference being that the blade of the angledozer can be set at an angle of about 30 deg. to discharge material to one side, whereas

FIG. 12.—BULLDOZER FOR REMOVING SOIL.

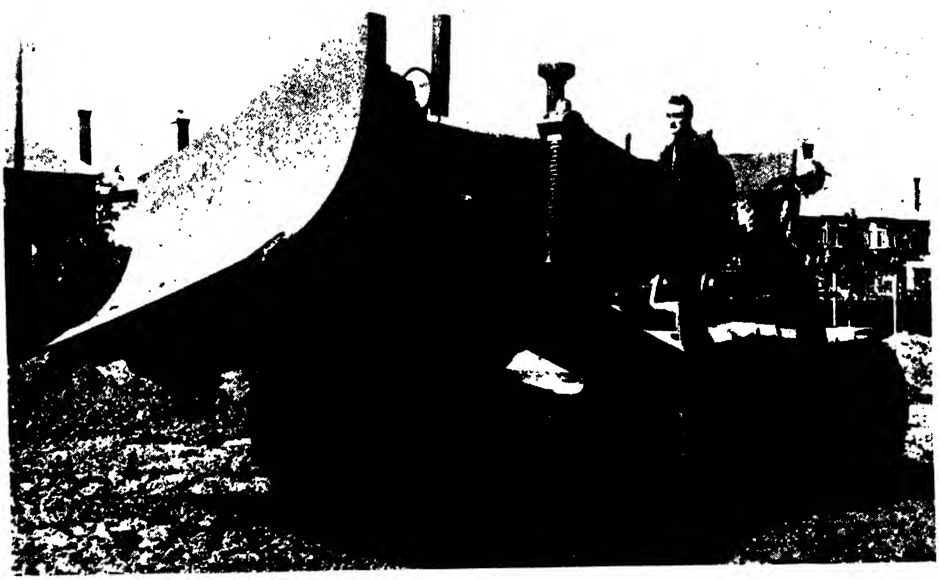


FIG. 13.—ANGLEDOZER FOR REMOVING SOIL.

the bulldozer blade is set squarely across the front. By their aid soil can be moved a distance of up to 150 ft. more economically than with other forms of earth-moving equipment. Although their action is simple, it is one that calls for a considerable measure of skill on the part of the driver if maximum efficiency is to be obtained. Special knowledge is required to determine the best application of these machines to any particular earthworks scheme.

POWER-OPERATED SCRAPERS.—The modern wheeled scraper (*Fig.* 14) is used for digging and transporting material up to a distance of about 500 yd. The machine consists of a mechanically-operated unit mounted on either two or four large pneumatic-tyred wheels coupled to a tracked tractor; it excavates, transports, and discharges the material. The machines are made with the following capacities to suit various tractors: 4 cu. yd., 6 cu. yd., 8–9 cu. yd., and 12–13 cu. yd. The machines are usually operated either by cable or hydraulically,

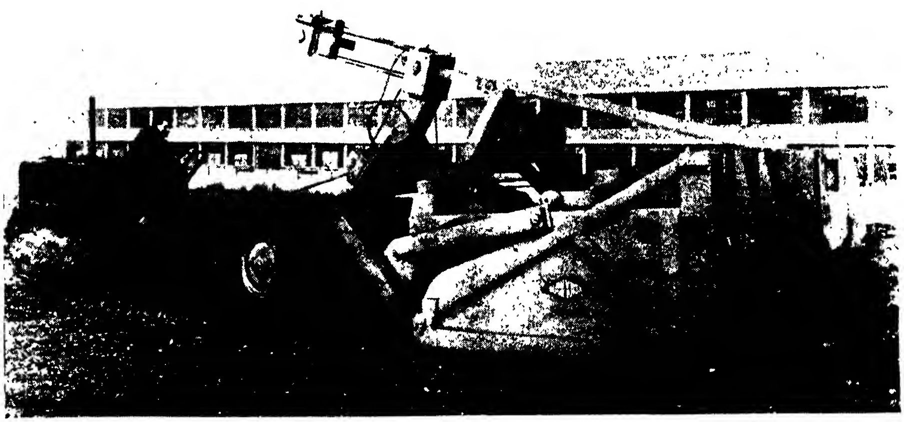


FIG. 14.—SCRAPER AND TRANSPORTER.

their work commencing after the bulldozers and angledozers have completed their job. Their digging action is not unlike that of a dragline bucket, the principle difference being that the latter can fill itself to capacity within a distance of approximately 10 ft. whilst a scraper working on the same material may require as much as 100 ft. Generally scrapers are only suitable for use with ploughable material or material that has been loosened by a scarifier; their success is due to the fact that they combine in a single unit the operations of digging and transporting, thus making them valuable for forming embankments and similar work.

ROTARY SCRAPERS.—These are comparatively small machines of about 1 cu. yd. capacity, mostly employed for filling areas where a large output is not required and where the haul is short. They carry part of their load in a bowl and part is pushed in front. They are not, however, as easily regulated as the wheeled scraper regarding depth of cut taken or thickness of layer spread.

SHEEPSFOOT ROLLERS.—These consist of a heavy, hollow, metal cylinder in sections about 4 ft. long and 4 ft. in diameter with feet extending 7 in. to 9 in. from its surface (*Fig.* 15). The feet are arranged in rows circumferentially around the cylinder with the feet in successive rows staggered. The rollers are made in sections which may be coupled together in tandem or parallel; a single section generally weighs from 3,000 to 3,500 lb. The cylinders are watertight and fitted

FIG. 15.—SHEEPSFOOT ROLLER.

with a plug so that they can be filled with water or dry sand, thus enabling the weight to be greatly increased when required. Two sections, either in tandem or parallel, can be pulled by a 78-h.p. tractor, whilst a 110-h.p. tractor can pull two such double sections. The speed at which the rollers are hauled affects the impact with which the feet strike the soil. In general, the best results are obtained and the least number of trips required at a speed of from 2½ to 3½ miles per hour.

Stabilised Bases.

Since the surface of a road is the only part which can be seen, defects which it may develop are frequently ascribed to the materials of which it is made, whereas in most cases they are due to weakness in the foundation reflected in the surfacing which generally conforms to any movement of the base. Local settlement or upward movement of the base may cause the surfacing to become uneven or to crack and, whilst it may be sufficiently strong temporarily to resist the stresses so created, it is only a matter of time before repetition of the stress may cause failure. With the exception of natural rock, no foundation can be said to be absolutely rigid, that is, to be unaffected by temperature, moisture, or loads. Where such foundations are absent it is important to ensure that the selected route provides the best available conditions of stability and uniformity of subsoil.

There has been evolved a laboratory method which enables the behaviour of various types of soil to be forecast with a reasonable degree of accuracy, and treatments to be prescribed to improve the bearing capacity of those that are unsatisfactory. This treatment is of primary importance in relation to embankments and foundations, and covers such points as the best method of compaction for various types of soil in order to restore the disturbed material as nearly as possible to its original density. The problem can be subdivided into three parts, namely, (1) Soil characteristics and the factors which influence its behaviour, (2) Foundation survey, or the examination of the ground over which the road has to be carried, and (3) Drainage.

The importance of the bearing power of the foundation has long been realised, and it was generally agreed that while sand and gravel made good foundations silt and clay did not. It is only within recent years that a method has been evolved whereby soils can be classified and the factors which influence their behaviour determined. Where such factors as weathering by air, temperature, or moisture are involved, soils, which to all outward appearance are of the same composition and apparently homogeneous, show marked differences when submitted to laboratory tests, and the properties, particularly the consistency, of any given soil depend entirely upon its moisture content. An American method of classifying soils according to their capacity to support wheel loads is given in Appendix III.

CHAPTER III

DESIGN

THE design of a concrete road comprises first, estimating the forces that will act upon it, and secondly, designing the road so that it will resist these forces with the maximum efficiency and economy. Experimental roads, research, and other investigations have removed in a large measure the necessity for guesswork in design, and it is now possible to determine with reasonable accuracy the most economical construction to meet given conditions of foundation and traffic.

Before the design and method of construction can be fully determined several factors must be examined. The most important are (1) The nature of the foundation, the situation of the road, and drainage ; (2) The weight and volume of traffic.

Foundation.

The foundation must support the slab uniformly. Either a uniformly soft or a uniformly hard foundation is satisfactory, but one that is soft in some places and hard in others will never give satisfactory results. The formation must be treated on its merits and regard paid to the general contour of the ground and to the provision of adequate drainage in low-lying areas.

Weight and Volume of Traffic.

A close approximation regarding the traffic to be carried can generally be obtained. Traffic may vary from 300 to 400 tons a day on a 16-ft. to 20-ft. wide housing estate road carrying builders' traffic to upwards of 20,000 tons a day on trunk or arterial roads where widths are not always proportionately greater. Further considerations are speed creating impact stresses, and the possibility of abnormal abrasion due to steel-tyred and tracked vehicles such as farm implements, horse-drawn vehicles in the neighbourhood of docks, and even to rubber-tyred vehicles in the case of omnibuses at bus stops.

Thickness of Slab.

Even if the distribution of stresses due to live loads and atmospheric influences were fully understood, assumptions must be made regarding fatigue and impact before a rational design can be prepared to satisfy a given set of conditions.

Several methods of computing these stresses have been proposed, and of these the theory advanced by Professor Westergaard* is the nearest solution that takes into account actual conditions and is of most value regarding the main features of slab design. The following are the principal conclusions to be derived from Professor Westergaard's investigations :

(1) That for most practical loading conditions the greatest stresses occur when the load is at an edge of the slab, and the next greatest when the load is at a corner.

(2) Other things being equal, there is a marked reduction of stress with increase of thickness. The maximum tensile stress in a 12-in. slab, for example, is only one-quarter to one-third the stress in a 6-in. slab under similar conditions.

* "Theory of Stresses in Road Slabs." Proc. United States Highways Research Board, 1926.

(3) The effect of changes in the modulus of foundation reaction is comparatively small.

Slabs should be designed so that the risk of cracking is reduced to a minimum; joints should either be as few as possible or provision made for transferring the load across the joint. The development of Professor Westergaard's analysis is too involved to describe in detail. The simple empirical formula developed by Mr. Clifford Older*, which assume the slab corners to be the critical portions, give results which closely approximate to computations made by Professor Westergaard's methods, as also do actual measured stresses and the behaviour of the Bates' test road sections and concrete roads in service. Mr. Older's formula take the following general form for pneumatic-tyred vehicles:

$$S = \frac{2{\cdot}4W}{D^2}, \quad \text{or } D = \sqrt{\frac{2{\cdot}4W}{S}} \qquad (1)$$

To evaluate foundation support this may be written

$$S = \frac{2{\cdot}4W.C}{D^2}, \quad \text{or } D = \sqrt{\frac{2{\cdot}4W.C}{S}} \qquad (2)$$

where S = unit stress in lb. per square inch, W = wheel load in lb., D = slab thickness in inches, and C = coefficient of foundation support. The unit stress S is derived as follows:

$$S = \frac{\text{Modulus of rupture in lb. per square inch}}{\text{Safety factor}} \qquad (3)$$

The modulus of rupture of concrete is generally assumed to be about one-seventh of its compressive strength. The safety factor must be left to the engineer's discretion and decided after consideration of the weight, volume, and speed of traffic for which the road is required both for present and future purposes. Generally, a safety factor of not less than 2 should be assumed.

The selection of the proper value of C must be based on estimation of the bearing value of the foundation soil, which may vary widely. Soft plastic clay soils may have a bearing value as low as 5 lb. per square inch, while very stable gravelly or chalk foundations may develop values as high as 50 lb. per square inch. The general practice is to adopt values of from 10 lb. to 30 lb. per square inch, although much higher values may occur on the more stable soils.

Professor Westergaard's analysis introduces a factor K which relates to the compressibility of the soil. A value of $K = 100$ means that when it is loaded with 1 lb. per square inch the soil will have a deformation of $\frac{1}{100}$ in. Since Mr. Older's formula agrees in general with Professor Westergaard's when $K = 100$, it is possible to determine values of C which will give the same stresses as are given by Professor Westergaard's analysis for various values of K. This has been done for various types of soil in *Table* IV.

As an illustration of the use of formula (2), assume that W = 4 tons plus 25 per cent. impact = 11,200 lb. and $C = 0{\cdot}84$ for hard foundation (*Table* IV).

Assuming a concrete of 1 : 2 : 4 nominal mix having a crushing strength of 4,200 lb. per square inch at 28 days, the modulus of rupture $= \frac{4{,}200}{7} = 600$ lb.

* The later version of Mr. Older's formula is given in "Engineering News-Record," Vol. 107, No. 2, 1931.

TABLE IV.

Nature of soil	Bearing value (Lb. per sq. in.)	Value of K in Westergaard's formula	Value of C for use in formula (2)
Very soft and plastic	5	50	1·09
Soft and plastic	10	100	1·00
Fairly hard	20	200	0·90
Hard	30	300	0·84
Very hard	40	400	0·80
Extremely hard gravel, rock, etc. . .	50	500	0·77

per square inch. With a factor of safety of 2 $S = \frac{600}{2} = 300$ lb. per square inch. Substituting in formula (2),

$$D = \sqrt{\frac{2{\cdot}4 \times 11{,}200 \times 0{\cdot}84}{300}} = 8\tfrac{3}{4} \text{ in.}$$

Table V contains recommendations for slab thicknesses based upon experience and current practice, and represent the views of most engineers in this country.

TABLE V.—SLAB THICKNESSES FOR VARIOUS SOILS AND TRAFFIC LOADS.

Type of subsoil	Thickness of slab in inches		
	Light traffic	Medium traffic	Heavy traffic
Loam; peat; sandy clay; silt	7	9	10–12
Virgin clay; well-consolidated embankments (other than clay)	6	7	9–10
Gravel; chalk; rock; well-graded sandy soils	6	7	8– 9

In terms of traffic and type of road the thicknesses given in *Table* VI may be safely assumed for concrete road slabs on all normal foundations.

TABLE VI.—THICKNESSES FOR ROADS FOR VARIOUS PURPOSES.

Type of road	Traffic (tons per day)	Slab thickness (inches)
Private streets; small housing estates; rural thoroughfares; etc.	Up to 500	6 to 7
Class II roads; large housing estates carrying heavy building traffic	Up to 5,000	7 to 8
Bus routes and less important Class I roads	5,000–10,000	8 to 9
Class I roads; motorways	10,000–15,000	9 to 10
City streets and busy thoroughfares	15,000–20,000	10 to 12

Slabs Thickened at Edges.

Developments in the design of cross sections during the past ten years have produced marked improvements in the roads constructed. A study of the stresses in typical road slabs resulting from load and temperature effects confirms the belief that progress has been made in the right direction, but it is clear that better designs are possible with the more complete knowledge at our disposal. The results of investigations by the Division of Tests of the United States Bureau of Public Roads * on the stresses that exist in concrete roads with certain combinations of load, temperature, and thickness, are surprising, and their conclusions are thought to be sufficiently well established for application in current design.

If loads alone are considered, maximum economy in the use of material is obtained with a thickened edge. While increased edge thickness results in a reduction of the edge stresses from an applied load, it also causes an increase in the edge stresses under certain conditions of restrained warping. Messrs. Teller and Sutherland's measurement of warping stresses at the edge of a 9-in—6-in.—9-in. test section showed the stresses to be higher in every instance in comparison with those at the same point in 6-in. and 9-in. slabs of uniform thickness. At times the difference was as much as 100 lb. per square inch for the 6-in. slabs of constant thickness, and 80 lb. per square inch for slabs of 9 in. constant thickness. Thickening the edges of the slab, however, is also closely connected with the design of corners, and tests show that thickening the edge of a slab 40 ft. or more in length will not tend to reduce transverse cracking but will help considerably to reduce corner cracking.

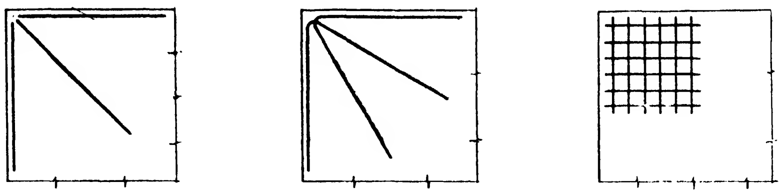
The thickened-edge slab with protected corners is used in America ; there are, however, many States that adhere to a slab of uniform section. The thickened-edge slab has certain advantages in the matter of economy ; for example, a 9-in.—6-in.—9-in. road 20 ft. wide requires 2053 cu. yd. of concrete per mile, whilst a uniform thickness of 7 in. requires 2283 cu. yd. per mile. American practice in the selection of shape of cross sections varies greatly, and some are much less efficient than others. Some States require a 2-ft. slope while others require 3 ft. and 4 ft. with corresponding variations in edge thickness. British engineers, however, have found no reason to depart from the use of slabs of uniform thickness, and their judgment is confirmed by the many successful roads that have been constructed in this way. Furthermore, climatic conditions and temperature ranges in the British Isles are less variable than in parts of the United States, for which reason the writers consider that a departure from the design adopted in this country would not be justified.

Other and simpler methods than edge thickening may be adopted which are known to give satisfactory results. One is to carry the slab under the kerb for a distance of 1 ft. 6 in. to 2 ft., measured from the kerb face so that traffic cannot approach sufficiently near the edge to cause excessive tensile stresses. A second method is to provide additional longitudinal reinforcement at the edges or, in the case of longitudinal joints, to construct these with a tongue and groove. A further safeguard to reduce corner cracking includes the provision of additional reinforcement at the corners in order to resist the high bending moments which are known to occur at these points. Suitable forms of corner reinforcement are shown in *Fig.* 16.

The need for thorough consolidation of the concrete at the corners of panels must be emphasised. For work carried out by hand the concrete at all corners should receive extra tamping with flat wooden rammers. There have been

* By L. W. Teller and Earl C. Sutherland, "Public Roads," Oct., Nov., Dec., 1935; Sept., Oct., 1936. E. F. Kelley, "Public Roads," July, 1939.

numerous instances where attention to this matter has given outstandingly good results.



⅝″ M.S. bars 5′0″ long, 2″ from top of slab.

⅝″ bars 10′0″ long bent to 60° about 2″ from slab surface

Mesh reinforcement overlapping to provide a double mesh at each corner not less than 3′0″ x 3′0″ in area about 2″ from slab surface.

FIG. 16.—CORNER REINFORCEMENT.

Size of Slabs.

The methods of construction usually adopted may be classified under three general headings, namely, (*a*) Full-width construction, (*b*) Alternate bay construction, and (*c*) Half-width or multiple-strip construction.

Full-width Construction.—In this method the slabs are laid the full width of the carriageway, usually with transverse joints spaced at regular intervals (see Chapter V). The most favourable widths are those not exceeding 15 ft., which is the approximate limit over which hand tamping can be efficiently carried out. Greater widths have been frequently undertaken, but in view of the difficulty of proper compaction such construction is seldom adopted except for foundations for surfacing materials other than concrete.

Alternate Bay Construction.—This method was probably evolved to prevent the development of transverse cracks common to construction without provision for expansion and contraction. By casting the slabs alternately the bays laid first take up initial shrinkage before the intermediate bays are laid, the carriageway being constructed for its full width. Experience showed that in order to prevent settlement of the slab caused by heavy traffic and the development of longitudinal cracks due to warping, it was necessary to install an efficient interlocking device at each transverse joint and also to ensure that the width between kerbs was kept within reasonable limits. Although more expensive than other methods of construction, it has certain advantages on soil of low bearing value, e.g. peat, and in districts subject to mining subsidence.

An example of this method of construction is the Althorpe by-pass road, Lincolnshire, on Trunk Road A18 constructed in 1932. The thickness is 10 in. The bays are 22 ft. wide between kerbs and 16 ft. long, with two layers of reinforcement each weighing 5 lb. per square yard. The Walker interlocking joint was used and the interval between the laying of the alternate bays was about twelve days. *Figs.* 17 and 18 show the metal form used for casting these joints and the edge of the concrete with the form removed. A section across very bad ground has subsided some 2 ft. to 2 ft. 6 in., but the slabs have remained together so accurately that the considerable longitudinal undulations in the road are almost imperceptible. The road carries a normal daily traffic of 10,000 tons, and although twelve years old it is entirely free from cracks throughout its length of approximately 3½ miles.

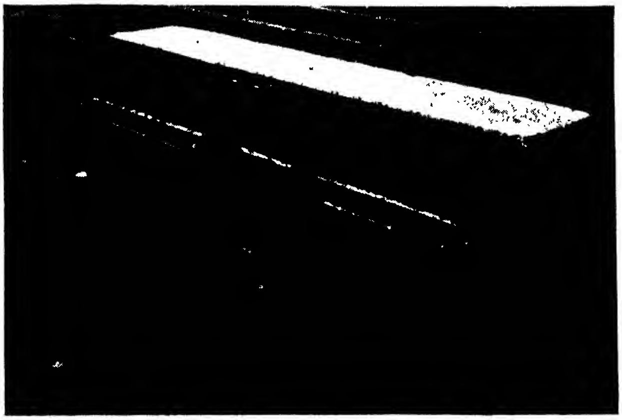


Fig. 17.—Form for Interlocking Joint.

It is essential in this type of construction to ensure that the prepared foundation for the intermediate bays is well protected against frost or the accumulation of water so that its bearing capacity, as well as that of the sub-base, is uniform throughout.

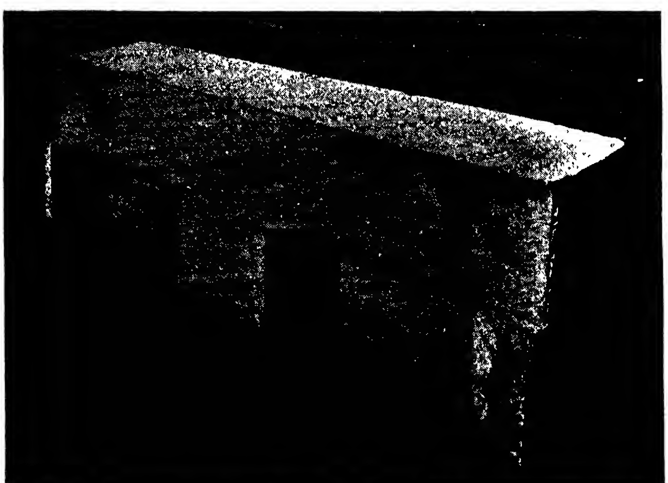


Fig. 18.—Interlocking Joint. Form removed.

The advantages of alternate bay construction are that (*a*) Carriageways may be constructed full width without longitudinal joints; (*b*) The camber can be accurately maintained; (*c*) Provided tamping and finishing are carried out in a longitudinal direction, smooth riding properties are obtained. Its disadvantages are (*a*) The road must be closed to traffic until completion; (*b*) The method is more expensive as the site must be traversed twice in order to complete the intermediate bays; and (*c*) The difficulty in restoring the foundation and sub-base to their original condition should continuous or heavy rainfall cause the intermediate bays to fill with water before they are concreted.

Half-width and Multiple-strip Construction.—This is a practical and economical method that is very widely adopted. It has the advantage that the road may be constructed in widths that ensure efficient compaction and finishing by hand or by machine, and it enables traffic to use the completed portion of the road or the half-width not under construction. Carriageways over 15 ft. and up to 30 ft. in width are generally laid in half-widths, whilst those over 30 ft. wide are constructed in three or more strips.

The advantages of this method of construction are (*a*) Transverse cracking is more easily controlled; (*b*) Tamping is simplified and more efficient, due to the comparatively narrow width; (*c*) It ensures greater accuracy of alignment and level, and therefore better riding qualities; (*d*) The road can be open to traffic throughout the construction period; (*e*) The longitudinal joints between the strips act as permanent traffic guides; (*f*) There is complete freedom from heaving or bursts; (*g*) Stresses caused by warping due to temperature changes are reduced.

Length of Slab.—The length of the slab will be determined by its thickness, the nature and bearing value of the foundation, the employment (or not) of reinforcement, and to some extent by the district in which the work is situated. The last factor is mentioned because the length of slabs constructed in humid and mild districts such as Ireland and the north-west coast of England may be appreciably increased compared with those laid in the south of England under similar conditions. The length and width of slabs are dealt with in more detail in Chapter V.

Single-Course and Two-Course Work.

Except in special circumstances, such as those indicated later, it is general practice to adopt single-course construction. Provided the aggregate is hard and durable and the concrete properly proportioned, mixed, and compacted, experience shows that well-designed one-course slabs will carry modern traffic for an indefinite period without undue wear. An experimental section 20 ft. wide laid by the Ministry of Transport in 1930 was composed of normal Portland cement, washed sand and ballast, in the proportions of 1 : 2 : 4 by weight. This road carried an average daily traffic of over 16,000 tons, and after seven years it was considered that during that period the rate of wear had been 1 in. in 200 years.

Occasions when it is either desirable or necessary to construct the slabs in two distinct courses include (*a*) When the road is subject to a considerable amount of steel-tyred traffic; (*b*) In comparatively small areas subject to considerable traffic; (*c*) When a coloured surface is required; this is a matter of cost and does not always apply in cases where the slab is less than 7 in. thick; (*d*) When the aggregate is not sufficiently hard or durable or may polish under traffic, in which case it is preferable to use this for the lower course and lay the top course with a harder aggregate; (*e*) When a coarse texture or roughened surface is required for traffic on gradients steeper than 1 in 18 (see "Roughened Surface Construction," page 92).

Width of Slab.

The division of the carriageway into strips of from 8 ft. to 12 ft. wide is now standard practice and has the advantages that (1) Efficient tamping may be undertaken either by hand or machine; (2) The formation of longitudinal cracks is prevented; (3) Roads that are being reconstructed need not be closed to traffic; (4) Stresses caused by temperature warping are reduced; and (5) The longitudinal joint or joints form efficient traffic guides when suitably treated.

CHAPTER IV

REINFORCEMENT

THE subject of the use of reinforcement for concrete road slabs is apt to be somewhat of a controversial nature because practical evidence of the results of its use is conflicting and lacks support from research work, which is insufficient to enable the subject to be studied with the same degree of accuracy as is possible with other types of reinforced concrete structures. The Technical Advisory Committee of the Ministry of Transport—Roads Department—in its report, " Concrete in Road Construction," published in 1933, mentions that a questionnaire issued to highway authorities in Great Britain revealed that 16 roads were of unreinforced concrete, 3 were reinforced at the top only, 82 were reinforced at the bottom only, and 31 were reinforced both top and bottom. There is no reason to think that post-war construction will see much alteration in these proportions.

An examination of concrete road specifications issued by the United States Highway Department in 1938 revealed that twenty States included reinforcement as standard practice, fifteen for special situations, four used marginal bars only, and five used no reinforcement. Owing to the comparatively high cost of steel in California and other Western States of America reinforcement is only used in special cases. German practice for motorway construction up to the year 1936 required top reinforcement weighing about 5 lb. per square yard ; thereafter the use of reinforcement was abandoned except for special cases. In place of this, the thickness of the slab was increased from 8 in. to 8¾ in. with results that are claimed to justify this construction.

The general opinion of highway engineers, and with which the writers agree, is that reinforcement justifies its use as an additional factor of safety, and that although it does not prevent cracking yet it serves a useful purpose in holding fractured portions together and preventing their settlement, thereby prolonging the life of the slab. Furthermore, although reinforcement may not entirely prevent the formation of cracks, yet should these occur they are more likely to be in the form of fine harmless cracks rather than one or two comparatively wide fractures.

The tensile stresses induced in a plain concrete road slab by the resistance of the foundation to shrinkage of the concrete during the process of hardening may, in certain circumstances such as lack of curing, too weak a mix, etc., cause the concrete to crack, and such cracks will open or close with changes of temperature and moisture. If, however, the slab is reinforced, then its contraction is not only resisted by the sub-base but also by the reinforcement to which the concrete is bonded, thereby increasing the tension in the concrete instead of reducing it. If the concrete is unable to resist these tensile stresses the bond between the steel and concrete will fail, causing fine cracks to develop at fairly regular intervals. Immediately this occurs all the tension carried by the slab is thrown on to the steel, and if this is not sufficiently strong it will fracture, because the axial tensile strength of normal road reinforcement is considerably less than that of an uncracked plain slab. If, however, the steel is sufficiently strong then the extra tension which it is called upon to resist will cause it to stretch even more than before cracking took place, and where it is bonded to the concrete, the latter must also stretch. If this tension is excessive more cracks will develop and will continue to form until the tensile strength of the concrete is not exceeded.

The amount and range of cracking will depend largely upon such factors as the friction between the slab and the foundation, the thickness and strength of the slab, and the superimposed loading, none of which has been considered in the foregoing discussion. These remarks, however, describe as simply as possible the effect of reinforcement, and they are supported by actual observation; many cases could be mentioned where reinforced slabs, after a period, exhibited fewer cracks than similar slabs without reinforcement but which in course of time developed cracks which made them indistinguishable in appearance from the latter.

The Report of the Road Research Board for the year ended March, 1937, contains interesting information regarding tests carried out on a number of small slabs to compare the cracking developed with various types of reinforcement. These tests showed that the presence of reinforcement of any of the types used had no effect in preventing the formation of cracks. On the other hand, the reinforcement proved of use in restricting the width of a crack when once formed.

Perhaps the most interesting series of experiments were those carried out by the Ministry of Transport at Harmondsworth, Middlesex, on the Colnbrook by-pass road to investigate—*inter alia*—the relative merits of unreinforced slabs and slabs with double and single reinforcement. The slabs were laid on a firm sub-base and carried a total average daily traffic of 16,000 tons (1935 census) on a road 20 ft. wide. Details of construction appeared in the Report for the year 1930 of the Technical Advisory Committee and interim reports published yearly up to 1936 contain the following conclusions: (1) The 6-in. slab with bottom reinforcement disclosed no advantage over unreinforced concrete; (2) The advantage of using double reinforcement was clearly shown, although the difference in the amount of cracking between this and other types of construction continued to diminish; (3) Cracks in unreinforced slabs spalled considerably, but those in the reinforced slabs underwent little change, being very narrow and free from spalling. Most of the spalling on the unreinforced slabs occurred during the first three months of 1936, or over six years after the road was constructed; (4) The use of additional reinforcement at the corners of slabs resulted in the prevention of corner cracking.

Position of Reinforcement.

Where a single layer of reinforcement is used the question of its position is important. It may be thought that if a single layer is to be used the best position for it is near the bottom of the slab, on the assumption that the slab acts as a beam should it be required to span areas on the sub-base which provide inadequate support. This is not so, for, owing to the continuity of the slab, the maximum bending moments may occur in the top over the points of support; therefore some reinforcement should be placed in the top where high stresses occur. Furthermore, the amount of reinforcement commonly used in road work is quite inadequate to resist stresses created by heavy wheel loads no matter in what position it may be placed. If a single layer of mild steel reinforcement is used its best position is 1½ in. to 2 in. from the top of the slab, and its weight should not be less than 7 lb. per square yard for slabs up to 8 in. thick.

It is impossible to make specific recommendations that can be applied to any given set of conditions. *Table* VII, however, may be used for general guidance and gives suggested weights and positions of mild steel reinforcement for various conditions of foundation, traffic, and slab thicknesses.

TABLE VII.—REINFORCEMENT FOR VARIOUS CONDITIONS.

Daily traffic (tons)	Foundation	Slab thickness (inches)	Weight of reinforcement (lb. per sq. yd.)	Position in slab
Up to 500	Bad	7	10	Top
	Medium	6	8	Top
	Good	6	7	Top
500 to 5,000	Bad	8	10	Top
	Medium	7	8	Top
	Good	7	7	Top
5,000 to 10,000	Bad	9	10	Top and bottom
	Medium	8	8	Top and bottom
	Good	8	7	Top
10,000 to 15,000	Bad	10	10	Top and bottom
	Medium	9	8	Top and bottom
	Good	9	7	Top and bottom

If thicknesses such as those recommended on page 24 are adopted, and joint spacing, compaction of the concrete, curing, etc., are suitable and properly carried out, reinforcement may be omitted in slabs constructed on subsoils composed of gravel, chalk, or rock whose bearing capacity is practically constant. In this connection it may be mentioned that experimental work regarding the stabilisation of foundation soils has provided information on suitable treatment to improve their stability with a view to eliminating arbitrary methods of deciding their bearing capacity. Results appear to indicate that it may be possible to reduce the thickness of slabs laid on a stabilised base which, in turn, may influence their reinforcement.

Amount of Reinforcement.

It will be gathered from the preceding discussion that reinforcement is primarily used to hold the edges of cracks together, and not necessarily to increase appreciably the load-carrying capacity or to prevent cracking. The reinforcements would have to be in two layers and in much larger amounts than normally used if it is intended to add considerably to the structural strength of the slab.

When a concrete road slab contracts its movement is resisted by the sub-base. At the centre of the slab the movement and sub-base resistance are zero. As the distance from the centre of the slab increases the contraction movement and sub-base resistance also increase until, if the slab is long enough, a point is reached at which resistance reaches a maximum and constant value. For a slab without reinforcement the maximum contraction stress, based on data provided by tests made at Arlington, U.S.A., is given by the equation

$$T_c = \frac{WLC_a}{24h} \qquad . \quad . \quad . \quad . \quad . \quad . \qquad (4)$$

in which T_c = tensile stress in concrete in lb. per square inch ;
W = weight of slab in lb. per square foot ;
L = length of slab in feet ;
h = depth of slab in inches ;
C_a = average value of the coefficient of sub-base resistance, which will depend on the nature of the sub-base, the slab thickness, and the change in temperature. A safe value is 2·5 based on a maximum daily range of temperature in the slab of 40 deg. Fahr.

Then, for a 6-in. slab having a length of 100 ft. and a weight of 75 lb. per square foot, $T_c = \frac{75 \times 100 \times 2{\cdot}5}{24 \times 6} = 130$ lb. per square inch.

For a reinforced slab the area of reinforcement can be found from

$$A_s = \frac{WLC_a}{2f_s} \qquad . \quad . \quad . \quad . \quad . \quad (5$$

in which W and C_a are the same as in (4) and

L = distance in feet between free joints (spacing of free transverse joints for computing longitudinal steel and spacing of free longitudinal joints for computing transverse steel) ;
A_s = effective cross sectional area of steel in square inches per foot of slab width ;
f_s = allowable unit tensile stress in the reinforcement in lb. per square inch.

If the reinforcement is to maintain in a tightly closed condition cracks that develop due to warping or contraction it is necessary to limit its elongation at these cracks to as small an amount as possible. The total elongation of steel subjected to tensile stress is dependent on the length that is free to elongate. The reinforcement is initially in bond with the concrete and, when a crack forms, the bond is destroyed over a certain length of steel. This length is then free to elongate under the stress induced by the resistance of the sub-base. However, the length over which the bond is destroyed is not known and therefore it is impossible to compute the total elongation corresponding to a given stress. This in turn makes it impossible to determine the maximum allowable stress in the steel that will ensure the maintenance of tightly-closed cracks.

The reinforcement should therefore be designed to limit the maximum width of cracks that may develop to as small a dimension as possible. The width of cracks, however, is dependent on the elongation of a certain length of steel and this elongation is, in turn, dependent not on the strength of the steel nor, at working stresses, on the yield point of the steel, but on its modulus of elasticity and the unit stress to which it is subjected. Since all grades of plain bar or wire reinforcement have approximately the same modulus of elasticity, it follows that the elongation in a given length is independent of the grade of steel and varies only with the unit stress. Therefore, in the determination of a safe allowable unit stress, consideration should be given to the maximum permissible elongation and to a certain extent to the yield stress.

In view of these considerations the best that can be done, until more information becomes available, is to select maximum allowable unit stresses that are reasonably conservative when considered in relation to the yield stress of steel.

It is then possible to compute elongations that may be developed under certain assumed conditions.

The minimum yield points or yield stresses for various grades of reinforcement are given in B.S. Nos. 785, 1144, and 1221, as follows:

	lb. per sq. in.	
Medium tensile steel	43,680	for bars up to 1-in. diameter
High tensile steel	51,520	,, ,, ,, ,, ,, ,,
Square twisted bars	70,000	,, ,, under ⅜-in.
	60,000	,, ,, ⅜-in. and over
Twin-twisted bars	54,000	
Expanded metal. . . .	50,000	

B.S. No. 785 at present gives no yield point for either mild steel or cold-drawn mild steel wire. The normally allowable working stress is about 50 per cent. of the yield stress with a maximum value of 27,000 lb. per square inch. The computed elongations for certain of these steels at such stresses are given in the following table for assumed lengths of free elongation of 12 in., 18 in., and 24 in., and a modulus of elasticity of 30,000,000 lb. per square inch.

Grade of reinforcement	Unit stress lb. per sq. in.	Elongation in length of		
		12 in.	18 in.	24 in.
		In.	In.	In.
Mild steel	18,000	0·0072	0·0108	0·0144
Medium-tensile steel	22,000	0·0088	0·0132	0·0176
High-tensile steel	25,000	0·0100	0·0150	0·0200
Twisted square bars and cold-drawn wire	27,000	0·0108	0·0162	0·0216

It is observed that the maximum elongation above is about two hundredths of an inch, which corresponds to a faintly discernible crack.

Assume that it is desired to find the amount of reinforcement required for a road slab of the following dimensions: Width, 12 ft.; thickness, 8 in.; spacing of transverse joints, 30 ft.; weight of slab, 100 lb. per square foot; allowable unit stress on steel, 25,000 lb. per square inch.

By formula (5), $A_s = \frac{WLC_a}{2f_s}$.

Longitudinal Steel:

$$A_s = \frac{100 \times 30 \times 2{\cdot}5}{2 \times 25{,}000} = 0{\cdot}15 \text{ sq. in. per foot width of slab} = 4{\cdot}6 \text{ lb. per square yard.}$$

Transverse Steel:

$$A_s = \frac{100 \times 12 \times 2{\cdot}5}{2 \times 25{,}000} = 0{\cdot}06 \text{ sq. in. per foot width of slab} = 1{\cdot}8 \text{ lb. per square yard.}$$

Thus the total weight of steel should be not less than 7 lb. per square yard, divided in the foregoing proportions of longitudinal and transverse steel.

The quantity of steel derived by the use of formula (5) agrees closely with that generally adopted. The final decision, however, rests with the engineer, who will be guided by his experience and judgment. *Table* XI is given for general guidance in connection with the type and spacing of joints and weight or reinforcement for road slabs laid on normal foundations. The weights given are for mild steel.

Placing Reinforcement.

To ensure that the reinforcement acts properly attention must be given to its accurate assembly and to its support so that its correct position is maintained during concreting. The reinforcement may be assembled on the site, or a mesh reinforcement conforming to the requirements of B.S. No. 1221 (1945) may be used. Mesh reinforcement is supplied in flat sheets or in rolls, but the former can be more accurately placed and kept in position. The following summarises the methods usually adopted to support the reinforcement and ensure that it is kept in its correct position.

SUPPORTING REINFORCEMENT ON A LAYER OF CONCRETE.—This method is frequently adopted although it has several disadvantages. A layer of concrete of the same proportions as those used for the remainder of the slab, and equal in depth to the specified distance of the reinforcement from the bottom of the slab, is spread on the sub-base. This is well tamped and the reinforcement laid thereon, followed by the concrete for the remaining depth. In the case of a double layer of reinforcement, one in the bottom and the other in the top of the slab, the required thicknesses of concrete are placed and tamped before each layer of reinforcement is placed.

A disadvantage of this method in the case of a single layer of reinforcement in the bottom of the slab is that the area of concrete on which the mesh is laid must be restricted in hot weather unless the remaining concrete is deposited within a few minutes. The reason for this is that the water content of concrete that is laid in a comparatively thin layer, usually not more than 1½ in. in depth, quickly evaporates in hot weather and if left uncovered may not have sufficient moisture to hydrate the cement. The addition of water to counteract this will weaken the concrete. The use of waterproofed paper, or damping the sub-base, will prevent the added water washing cement out of the slab into the sub-base, but will not compensate for the loss of strength and density due to the addition of extra water. A reasonable alternative would be the application of moisture in the form of cement grout, thereby maintaining workability without materially affecting the water-cement ratio.

SUPPORTING REINFORCEMENT ON METAL PIPES OR TUBES.—This method, if carefully applied, is reasonably efficient for prefabricated mesh reinforcement. One end of the reinforcing mat is bedded on a layer of concrete about 1½ to 2 in. thick and supported at a distance of about 3 ft. from the same end by a metal tube or pipe 2 in. in external diameter and slightly longer than the width of the mat. Concrete is deposited through the mesh until the reinforcement is entirely surrounded and the 3-ft length filled; the tube is then rolled forward a sufficient distance at a time to support the mat just ahead of the concreting gang. This method is open to the objection that if the pipe is drawn too far ahead the reinforcement tends to sag. In addition, there is a risk of disturbing the foundation if the pipe is pulled instead of being rolled over the sub-base. If clinker is used as a sub-base it may be loosened and tamped into the concrete.

SUPPORTING REINFORCEMENT ON BENT BARS.—Probably the best method of supporting reinforcement is to employ bent bars, as illustrated in *Figs.* 19 and 20. This method depends for its efficiency on the strength of the steel bars and the bearing capacity of the foundation.

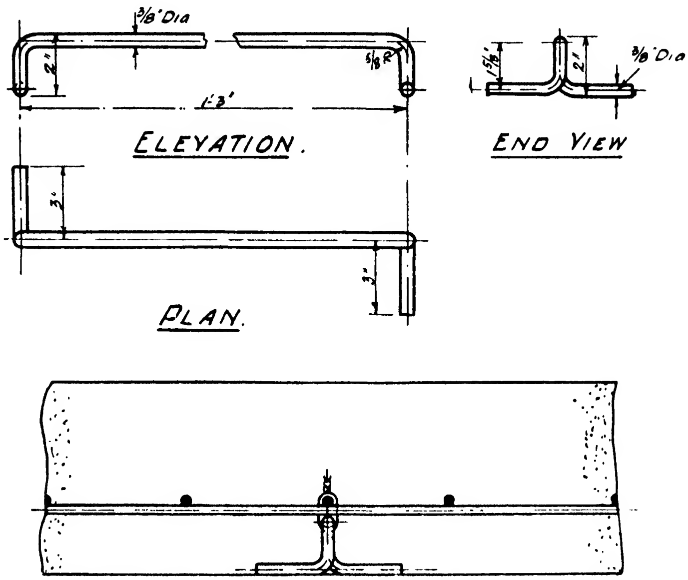


FIG. 19.—SUPPORT FOR REINFORCEMENT.

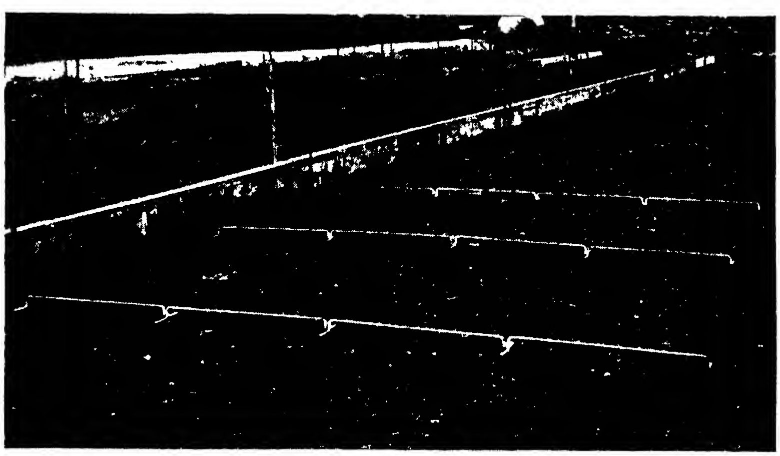


FIG. 20.—SUPPORTS FOR REINFORCEMENT.

REINFORCEMENT IN VIBRATED CONCRETE.—As rigid a mat of reinforcement as possible should be used if the concrete is to be vibrated; hence there would appear to be some advantage in using stiff bars or wires and increasing the spacing to suit the larger diameter. Provided there is reasonable rigidity in the mat the metal supports described in the previous paragraph are suitable. The supports must be stout, otherwise, to prevent movement, the bars must be pinned down at fairly frequent intervals by means of hooked spikes driven well down, if the formation allows this to be done.

CHAPTER V

JOINTS

JOINTS are required in concrete roads for the purpose of reducing as much as possible the stresses resulting from causes other than those due to applied loads, and their provision is desirable so that the strength of the concrete slab may be conserved to the fullest extent in order to resist the more frequent and severe stresses caused by traffic loads. A joint is generally a potential plane of weakness, and if badly constructed or wrongly placed may not only seriously affect the load-carrying capacity of the road but may result in high maintenance charges. Joints should be so designed and spaced as to permit the entire roadway to expand, contract, and warp with a minimum of restraint. They may be classified, according to the stresses they are intended to relieve, into three categories, namely,

(1) Expansion joints designed to provide space in which unrestrained expansion can occur and so control the direct compression stress caused by expansion of the concrete due to changes in temperature and moisture content.

(2) Contraction joints designed for the relief or control of the direct tensile stresses caused by restrained contraction due to changes in temperature and shrinkage.

(3) Joints designed to permit warping to occur, thus reducing restraint and controlling the bending stresses developed by restrained warping.

Obviously a joint may, and frequently does, perform all these functions. An expansion joint, for example, may permit unrestrained expansion, contraction, and warping, while a joint of the so-called contraction type may actually benefit the slab more by its ability to relieve warping stresses than by its intended purpose of relieving direct tensile stresses caused by contraction.

Expansion and Contraction due to Changes of Temperature.

It is generally accepted that the coefficient of linear expansion for design purposes for ordinary structural concrete is 0·0000055 ft. per foot length per degree Fahrenheit. In Great Britain the average air temperature varies about 75 deg. F. during the year, and this controls the magnitude of the annual change in length caused by temperature changes. In the case of a road slab 100 ft. long the maximum change in length which could occur due to temperature, assuming that the temperature of the concrete varied with the air temperature, would be $0{\cdot}0000055 \times 75 \times 100 \times 12 = 0{\cdot}5$ in.

Expansion and Contraction due to Changes in Moisture Content.

Concrete expands and contracts due to changes in moisture content. It remains expanded so long as it is kept wet and shrinks when the moisture content is decreased. The change in length from the bone dry to the saturated condition varies with the density and quality of the concrete. For 1 : 2 : 4 structural concrete the change in length is from 0·03 to 0·05 per cent. Assuming the higher figure, although it is not likely to be met in practice, a road slab could expand or contract 0·6 in. in 100 ft., and this must be considered when deciding the width of expansion joints.

Fig. 21 shows the average seasonal and daily changes in length of a 100-ft. slab caused by variations in temperature and moisture content based on observed movements in America. The length changes are in inches. and the graph shows that the rise in temperature from winter to summer caused an expansion of about 0·45 in. During the same period a loss of moisture occurred which caused a contraction of about 0·15 in. The net result of the combined annual volume changes was an expansion of about 0·30 in. from winter to summer. The daily changes in length are approximately 0·03 in. in winter and 0·08 in. in summer. The maximum surface temperature recorded during this period was 112·5 deg. F. and the minimum 10 deg. F. It has been shown that a 6-in. slab is more

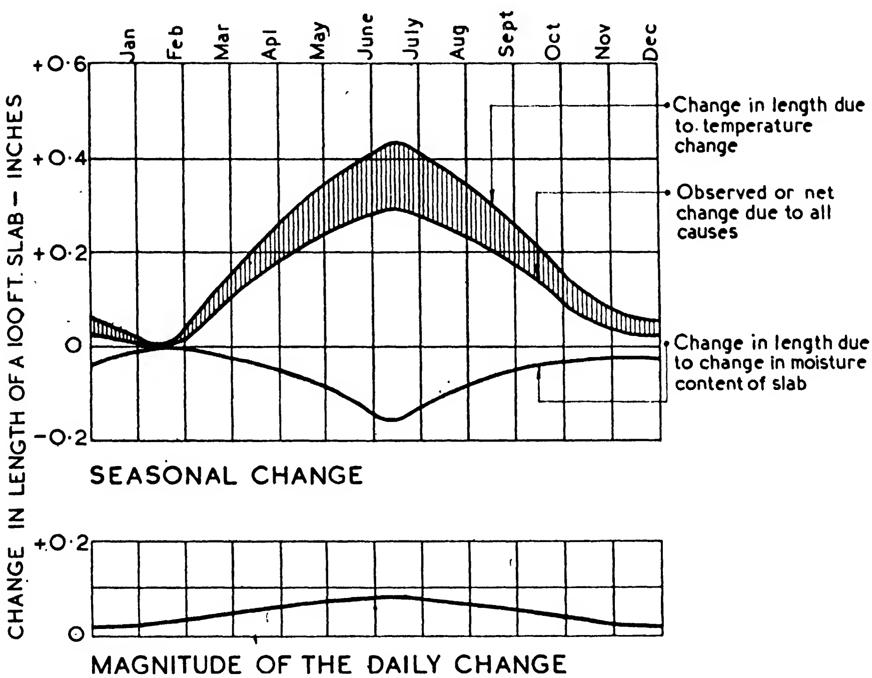


FIG. 21.—AVERAGE CHANGE IN LENGTH DUE TO VARIATIONS IN TEMPERATURE AND MOISTURE CONTENT.

responsive to variations in air temperature than is a 9-in. slab, although the actual temperature difference between the upper and lower surfaces is greater for the thicker slab. The maximum difference observed at any time in the 6-in. slab was 24·3 deg. F., while in the 9-in. slab it was 31 deg. F. Similar investigations undertaken by the Road Research Board, and described in its report for the year ended March 1938, agree closely with these American results.

The maximum possible movement due to moisture is 0·6 in. and to temperature 0·5 in., a total of 1·1 in. for a slab 100 ft. long. Experience leads to the view that provision to this extent is unnecessary. Records taken by the Bureau of Public Works of America over a period of five years show that the change in length of a road slab caused by variations in moisture content ranges from about $\frac{1}{8}$ in. to $\frac{1}{4}$ in. in a length of 100 ft. Furthermore, it is improbable that maximum temperature and maximum moisture conditions will occur at the same time, so that with these considerations in mind a suitable allowance is $\frac{3}{8}$ in. per 100 ft. of slab.

Contraction Joints.

Restrained contraction will cause tensile stresses in the slab, and restraint will be developed by friction between the slab and its foundation. When these stresses exceed the strength of the concrete, transverse cracks will develop unless the length of the slab is kept within reasonable limits by transverse joints.

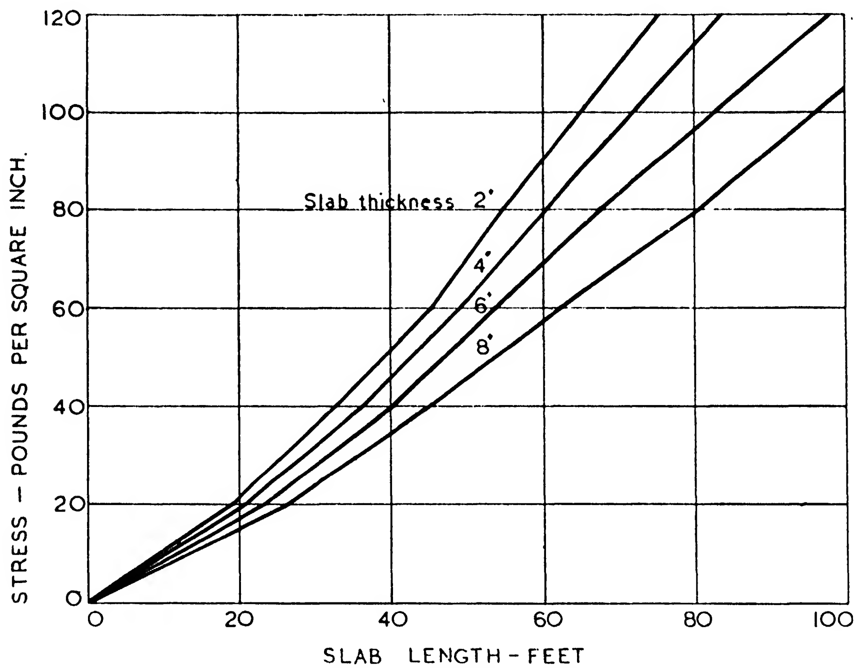


Fig. 22.—Effect of Length and Weight of Slab on Stresses caused by a Change of Temperature of 100 deg. Fahr.

The spacing of contraction joints, therefore, unlike that of expansion joints, will be determined by the permissible unit stress on the concrete. If this is restricted to a low value, as is most desirable because of its direct effect on the load-carrying capacity of the slab, say 50 lb. to 60 lb. per square inch, test data indicate that the spacing between contraction joints should be kept small, possibly 20 ft. to 30 ft. depending upon the width and depth of the slab.

In slabs of moderate length the tensile stresses resulting from contraction will not be large for sub-base soils composed of granular material that has been well rolled and consolidated. The thicker the slab the lower will be the unit stress from this cause, other conditions being the same. *Fig.* 22 shows the stress intensity for concrete slabs 2 in. to 8 in. thick laid on a prepared sub-base of silty loam. This soil was thoroughly compacted by a 5-ton tandem roller and great care was taken to obtain an even and smooth surface.

Joints to Permit Warping.

A difference in moisture or temperature in the top or in the bottom of a road slab will produce curvature or warping, which has two important effects. If the slab were completely free and without weight it would assume a distorted shape without resistance and no stresses would result. Actually hardly any part of the slab is free to adjust itself, and restraint caused by the weight of the slab and by the reaction of the sub-base is always present.

Warping has two important effects. In the first place it alters the condition of the sub-base support and thus affects the magnitude of the stress produced by a given wheel load. In the second place, because of the restraint mentioned, certain of the stresses arising from temperature warping are equal in importance to those produced by wheel loads. The longitudinal tensile stress in the bottom of a slab 20 ft. long by 10 ft. wide caused by restrained temperature warping may amount to as much as 350 lb. per square inch at certain periods of the year, the corresponding stress in the transverse direction being approximately 125 lb. per square inch. These stresses are in addition to those produced by wheel loads. *Tables* VIII and IX show the longitudinal warping stresses developed in experimental road slabs and measured by the Division of Tests, United States Bureau

TABLE VIII.—LONGITUDINAL WARPING STRESSES AT THE EDGE OF TWO 20-FT. ROAD SLABS OF UNIFORM THICKNESS.

Temperature difference between top surface and underside at edge of slab		Observed longitudinal warping stresses	
6-in. slab	9-in. slab	6-in. slab	9-in. slab
Deg. Fahr.	Deg. Fahr.	lb. per sq. in.	lb. per sq. in.
18	25	209	191
20	26	252	306
20	31	320	329
19	25	266	213

TABLE IX.—LONGITUDINAL WARPING STRESSES IN 10-FT. AND 20-FT. CONCRETE ROAD SLABS 6 IN. THICK AT THE CENTRE AND 9 IN. THICK AT THE EDGES.

Maximum air temperature		Maximum longitudinal warping stress in lb. per square inch			
		Interior of slab		Edge of slab	
Date	Deg. Fahr.	20-ft. length	10-ft. length	20-ft. length	10-ft. length
April 26 . .	68	307	132	—	—
May 1 . .	74	376	142	—	—
,, 2 . .	71	—	—	121	68
,, 13 . .	83	287	81	—	—
,, 14 . .	90	—	—	278	21
,, 28 . .	83	429	151	—	—
June 1 . .	90	—	—	354	46
,, 11 . . .	94	414	130	—	—
,, 25 . .	97	—	—	283	51

of Public Roads. Investigations further showed that at transverse joints the panels appeared to warp freely but that at longitudinal joints there was a tendency for the weight of the slab to force the central area to lie flat and prevent it from curling, thus causing the slab to crack. It was found that if the stresses caused by restrained temperature warping are to be properly controlled the length and width of the slab panels must be small.

Further investigations are necessary to determine maximum dimensions for various slab thicknesses. The present data indicate that a satisfactory control of warping stresses would ordinarily be obtained if the maximum dimensions of the slab were 10 ft. or 12 ft., indicating that the interval between warping joints should be of the same general order.

The present tendency for reinforced carriageways is to construct slabs 10 ft. to 12 ft. in width provided with transverse planes of weakness or dummy joints at about 15-ft. intervals and expansion joints not less than 60 ft. apart, and, so long as these are designed for load transference, cracking should be greatly reduced if not eliminated.

Efficiency of Various Types of Joints.

Comprehensive investigations were also undertaken by the United States Bureau of Public Roads to ascertain the efficiency of various types of joint, particularly those in which some means of load transference is incorporated. For this purpose ten road slabs were constructed, each 40 ft. in length, 20 ft. in width, and of a particular cross section, and each slab was divided by a longitudinal and transverse joint from those adjoining it. The concrete was uniform throughout the group and all the slabs were unreinforced. Special efforts were made to obtain uniformity of sub-base. The concrete mix by dry rodded volume was 1 : 2 : 3½, the average compressive strength at 28 days was 3,525 lb. per square inch, and the flexural strength was 765 lb. per square inch. The average fineness modulus of the sand was 3·26 and of the stone (which was graded from 2¼ in. to ¼ in.) 7·65. The joint efficiency values given in *Table* X are based on a comparison of the stresses at the side of the slab with those occurring in the middle of the slab.

TABLE X.—EFFICIENCIES OF VARIOUS LONGITUDINAL JOINTS FOR CONTROLLING THE STRESSES CAUSED BY LOADS PLACED NEAR THE JOINT EDGES.

Section No.	Type of joint	Diameter and spacing of dowel bars	Joint efficiency (per cent.)
3	Rectangular tongue	½ in. at 60-in. centres	78
5	Triangular tongue	½ in. at 60-in. ,,	75
10	Corrugated	½ in. at 60-in. ,,	72
9	Plain butt with tarred felt strip . .	¾ in. at 24-in. ,,	52
2	Plain butt with tarred felt strip . .	¾ in. at 48-in. ,,	51
4	Rectangular tongue	None	50
1	Plain butt with tarred felt strip . .	¾ in. at 60-in. ,,	47
6	Plane of weakness	½ in. at 60-in ,,	44
8	Plain butt with tarred felt strip . .	¾ in. at 36-in. ,,	42
7	Plane of weakness	None	39

In concrete road construction the dowels that cross the longitudinal joints are nearly always bonded to the concrete and are usually called "tie bars," although they are more exactly described as dowels in bond when they are called upon to withstand shearing forces. It will be noted from *Table* X that the rectangular and triangular tongued joints with ½-in. dowel bars were the most efficient ; also that the rectangular tongue joint with no dowels was more efficient than a plain butt joint with dowels at 36-in. centres, and approximately equal in efficiency to plain butt joints with dowels at 48-in. and 24-in. centres. It was shown that the dowelled transverse joints as built and tested had the following weaknesses. (1) The individual units were too widely spaced and were not stiff enough effectively to transfer loads of the magnitude involved under the conditions of the tests. (2) It is difficult to obtain complete and perfect embedment of a dowel bar. (3) Even if perfect embedment were obtained the unit bearing stress on the concrete is apt to be excessive when heavy loads are applied on one side of the joint. The closest dowel spacing tested was 18 in., and it was shown that for dowel size, joint openings, slab thicknesses, and loads as used in the tests, this spacing was too great.

The conclusions to be drawn from these tests are :

(1) The most critical stress caused by a load applied at a joint but away from a corner is that directly under the load in a direction parallel to the joint. It is especially desirable to control these stresses along a longitudinal joint so as to limit the combined load and warping stress to a value that will be unlikely to cause transverse cracking.

(2) The dowelled transverse joints tested were effective in relieving the stresses caused by expansion, contraction, and warping. They were not particularly effective, however, in controlling the stress caused by a load applied near the joint.

(3) The continuous dowel plate used appears to have considerable merit as a means of load transfer. The joint as used in the tests offers more resistance to expansion and contraction than is desirable, and for this and other reasons a further study of the type should be made.

(4) Interlocking of the aggregate in the weakened plane or dummy joint cannot be depended upon to control load stresses. Even when this joint is held closed by bonded steel bars, there is a wide variation in the value of the critical stress caused by a given load from side to side of the joint and from point to point along it. For this reason it appears necessary to provide independent means for load transfer in plane-of-weakness joints.

(5) The joints of the tongue-and-groove type that were held closed by bonded steel bars were the most efficient structurally of any of those tested. It appears, however, that certain modifications of the designs might improve their action by permitting the slabs to warp more freely and at the same time maintaining the bearing between the tongue and the groove.

Spacing of Joints.

The ideal interval between joints is the maximum at which no intermediate cracks will form. This will depend upon the tensile strength of the concrete, the weight of the slab, the sliding friction between the slab and its sub-base, and to some extent upon the amount of reinforcement.

Although some formulæ have been produced which give an approximate indication of spacing it is better to determine such dimensions by observation and experience and with regard to the situation of the road and the foundation on which it is placed. *Table* XI may be used for general guidance on the spacing of joints; this has been found to be satisfactory in this country. The last column of the table includes suggested treatments of transverse joints for purposes of load transference for roads that are subject to medium traffic constructed on foundations of doubtful load-bearing capacity.

TABLE XI.—SPACING OF JOINTS.

Slab thickness (in.)	Reinforcement	Max. width of slab (ft.)	Type and spacing of contraction joints	(*a*) Width and spacing of expansion joints and (*b*) Treatment for load transference
7	None	10	Interlocking joint at 12-ft. intervals	(*a*) $\frac{3}{8}$-in. wide at 60-ft. intervals. (*b*) $\frac{1}{2}$-in. dowel bars at 18-in. centres.
8	,,	12	Do. at 15-ft. intervals	(*a*) $\frac{1}{2}$-in. wide at 60-ft. intervals. (*b*) 4-in. by $\frac{1}{4}$-in. dowel plate or $\frac{5}{8}$-in. dowel bars at 12-in. centres.
8	,,	15	Do. at 15-ft. intervals	(*a*) $\frac{1}{2}$-in. wide at 60-ft. intervals. (*b*) 4-in. by $\frac{1}{4}$-in. dowel plate or $\frac{3}{4}$-in. dowel bars at 12-in. centres.
9	,,	15	Do. at 20-ft. intervals	Do.
10	,,	15	Do. at 20-ft. intervals	Do.
7	Single layer, 7 lb. per sq. yd.; in top portion of slab	10	None required	(*a*) $\frac{3}{8}$-in. wide at 25-ft. intervals. (*b*) $\frac{1}{2}$-in. dowel bars at 18-in. centres.
8	do.	12	,, ,,	(*a*) $\frac{1}{2}$-in. wide at 30-ft. intervals. (*b*) 4-in. by $\frac{1}{4}$-in. dowel plate or $\frac{3}{4}$-in. dowel bars at 12-in. centres.
8	Double-layer each 7 lb. per sq. yd.	15	,, ,,	(*a*) $\frac{1}{2}$-in. wide at 35-ft. intervals. (*b*) as for 7-in. slab.
9	do.	15	,, ,,	(*a*) $\frac{1}{2}$-in. wide at 40-ft. intervals. (*b*) do.
10	do.	15	,, ,,	(*a*) $\frac{1}{2}$-in. wide at 40-ft. intervals. (*b*) do.

Joint Fillers.

Considerable attention has been directed in recent years to the development of more satisfactory materials for filling and sealing expansion joints. A fully efficient material must be very elastic and able to accommodate itself to the movement of the slab without appreciable extrusion and must always maintain contact with the concrete, so as to prevent the entrance of either water or other foreign materials. Furthermore, it must be able to maintain these qualities for a considerable period of time without appreciable deterioration, be easy to install, and be of relatively low cost. Although no material has yet been introduced which fully satisfies all these requirements, considerable progress has been made. The following is a summary of the expansion joint fillers most commonly used.

CORK BOARD.—This is a very resilient material and has been proved efficient under test. An efficient sealing compound is required to keep the joint properly protected and also to allow for the gradual compression of the cork which may take place. It would be interesting to investigate the possibilities of a more highly compressed cork than is usually supplied.

FIBRE BOARDS.—These generally consist of a fibrous material such as shredded bamboo impregnated with bitumen. They are resilient, do not extrude, and have proved efficient. A sealing compound not less than ¾ in. in depth at the top of the joint is necessary.

RUBBER.—This has all the elasticity necessary but deteriorates, especially at the surface, under the severe conditions imposed by a combination of weather and traffic. If it is heavily compressed its recovery, on release, may be too slow.

RUBBER COMPOUNDS.—In order to overcome the objection of high cost of pure rubber products various compounds have been developed to which cheaper materials are added. The more common of these ingredients are ground cork, ground mica, mineral powders, tar, asphalt, etc. That some of these materials and compounds have considerable merit is indicated by the number of instances in which their use has given satisfactory results. Other results indicate that as a class the rubber compounds are still in the experimental stage and more definite knowledge is required on how and under what conditions they can be successfully used.

SPONGE RUBBER.—This has been used for about ten years as a joint filler. Inspection of sixteen roads on which it has been used indicates that, where fully protected by a tight seal, its behaviour has in general been satisfactory for a considerable period, but where no effective seal has been provided the filler shows appreciable deterioration and loss of elasticity after about three years' service. The type of sponge rubber used has sealed cells.

PREMOULDED BITUMINOUS FILLERS.—These fillers are the most commonly used, generally because they are the cheapest. There is a tendency for the filler to extrude when the joint closes, forming ridges on the surface which are eventually rolled out by traffic, making it necessary to refill the joints at intervals. There is generally a lack of resilience in these fillers by reason of which a space is left after compression is released, in which foreign matter can lodge and through which surface water will seep to the foundation. Nevertheless, a well-made premoulded filler, in which a certain amount of elasticity has been incorporated and on top of which a sealing compound is placed, has met with considerable success.

METAL CAVITY.—These metal joints require no filler, room for expansion being provided by an air cavity extending almost the full depth of the slab. These joints are described later and shown in *Fig.* 30.

SOFT WOOD.—This has been used with good results but would appear to be of greater value if a sealing compound is superimposed. Not being particularly resilient, its use is limited to slabs of short length, that is, when the joints are frequent, and it could not therefore be recommended when expansion joints are separated by a series of contraction joints.

Generally speaking, the type of filler to be used depends partly on the design of the slab and partly on the knowledge of the type of traffic. Obviously maintenance of joints on a housing estate should not be such a serious question as on a road with heavy traffic, and it may well be that the more expensive fillers will prove their value in the latter case, especially over a period of time.

Types of Joint.

Many types of joint have been tried from time to time, most of which are reasonably cheap and efficient. The ideal joint that is both economical and efficient, particularly for expansion and watertightness, has, however, not yet been found, but considerable progress has been made and there are indications that in the near future these difficulties will be overcome. In any case the most suitable type largely depends upon judgment and experience until more exact data are available. The following notes briefly describe the principal features of the joints most commonly used.

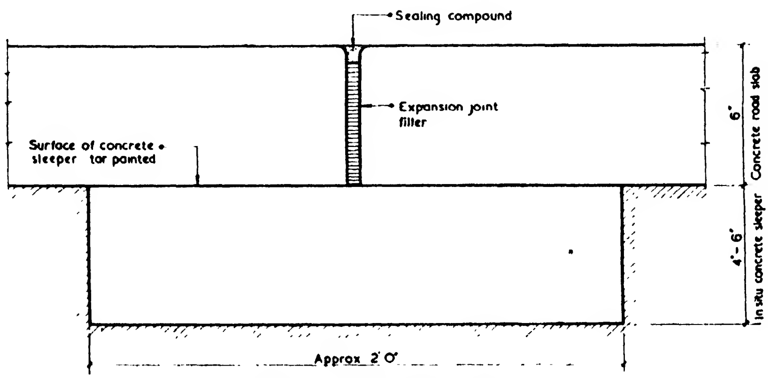


FIG. 23.—SLEEPER JOINT.

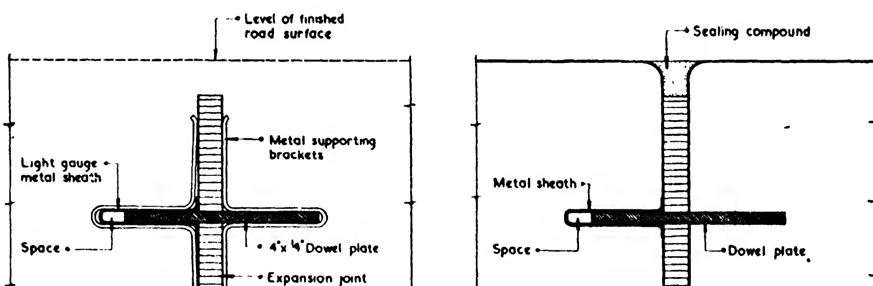


FIG. 24.—DOWEL-PLATE JOINT.

BUTT JOINT.—This is probably the most widely used, being generally adopted for forming transverse and longitudinal joints. In the case of the former its use is mostly confined to alternate bay construction where it acts as a contraction joint, serving a similar purpose in the case of longitudinal joints dividing carriageways into two or more widths. The joint, although one of the simplest to construct, frequently gives trouble due to faulty workmanship. It is important that the timber bulkhead against which the concrete is placed is exactly vertical and securely held in position, that the top edge of the joint is finished level with that of the bulkhead, and that the concrete for a distance of at least 6 in. from the joint is thoroughly compacted.

SLEEPER JOINT.—The sleeper joint (*Fig.* 23) is seldom used in this country although it has advantages for concrete paving on embankments and on foundations of doubtful bearing capacity where distribution of load is a consideration. It has the following disadvantages: (1) Difficulty in ensuring that the bearing capacity of the sleeper trench is equal to that of the sub-base. If it is less then its value as a means of load support is negligible, whilst, if it is greater, shearing stresses are induced in the slab at the points of support. (2) In certain circumstances moisture may collect under the sleeper due to "sleeper action" arising from continuous traffic, thus destroying its bearing capacity.

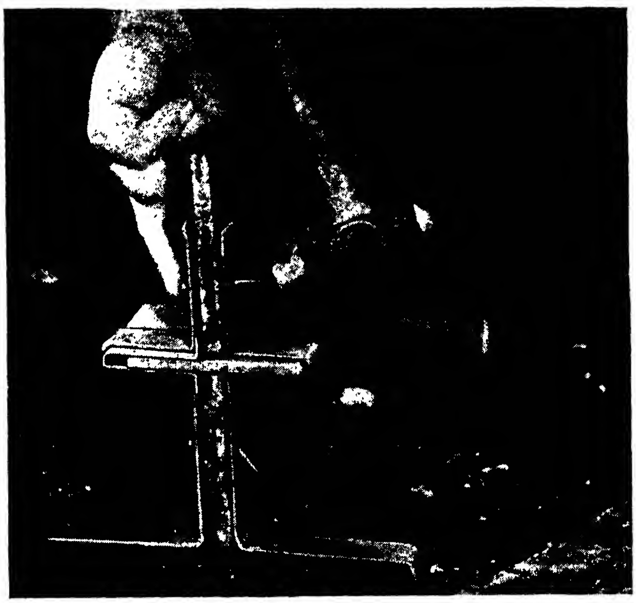


FIG. 25.—ASSEMBLING A DOWEL-PLATE JOINT.

DOWEL-PLATE JOINT.—A continuous mild steel plate about 4 in. wide by ½ in. or ⅜ in. thick provides a very efficient means for reducing deflection at joints due to wheel loads, but it offers a somewhat high resistance to the warping action of the slab if joint spacing is excessive. From the practical standpoint the advantages of this type of joint (*Fig.* 24) are ease of assembly, alignment, and support; furthermore its weight is less than the usual ¾-in. dowel-bar construction required for the same conditions. Freedom for slab movements at transverse expansion joints is provided by means of a light-gauge metal sleeve which fits over the unbonded or free portion of the plate. The expansion joint material is held in position by light metal supports the ends of which are pressed into the sub-base, thus holding the joint securely in position during concreting operations. *Fig.* 25 shows the joint components assembled ready to be placed in position to form an expansion joint. This type of joint may readily be adapted for use in contraction joints.

DOWEL-BAR JOINT (*Fig.* 26).—This is generally used for transverse expansion and contraction joints. Its efficiency in relieving stresses caused by expansion, contraction, and warping is satisfactory, but its effectiveness as a means of transferring load from one slab to another is not always satisfactory in situations where the surface is either weak or subject to moisture changes. Tests show that in this respect it is not as efficient as a dowel-plate joint. To provide freedom for the slabs to expand and contract, half the length of each dowel bar is given a thick coat of bituminous paint or a wrapping of stout paper, the remaining half of the bar being untreated and bonded with the concrete (see *Fig.* 26). For expansion joints, holes must be punched in the filler through which the bars are passed and their sliding or free end fitted with a light metal or cardboard cap about 4 in. long and slightly larger in diameter than the bar. The closed end of the cap is filled to a depth of about 1 in. with soft compressible material such as cotton waste into which the bar can thrust when expansion takes place. Dowel bars

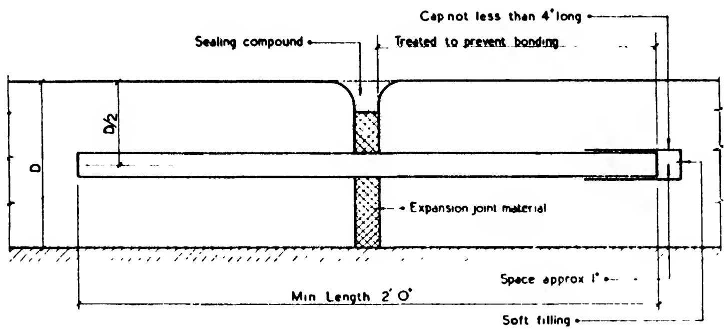


FIG. 26.—DOWEL-BAR JOINT.

generally vary from 2 ft. to 3 ft. in length and from $\frac{5}{8}$ in. to 1 in. in diameter. Their spacing for main road work is usually at 12-in. centres; for light-traffic roads $\frac{5}{8}$-in. bars at 18-in. centres are generally sufficient.

TONGUE-AND-GROOVE JOINT.—This is an efficient, inexpensive, and simple means of load transference for all joints other than expansion joints. As timber forms are generally employed to form the tongue, necessitating their removal before the joint can be completed, it is restricted to longitudinal joints and to alternate bay construction. This restriction is overcome in America by means of a light metal pressing (about No. 29 gauge) which is built into the concrete as the work proceeds. The metal pressing is made with a tongue having the required dimensions and is usually about $\frac{1}{2}$ in. less in depth than the slab. It is fitted with a removable metal cap to allow the groove to be formed, and is held in position on the sub-base by a few metal pins driven through holes punched in the tongue. For slabs 7 in. or more in depth the tongue is usually constructed to the dimensions shown in *Fig.* 27, whilst for 6-in. slabs a semi-circular or triangular tongue is satisfactory.

INTERLOCKING JOINT.—This type of joint, developed by the late Mr. J. H. Walker, M.Inst.C.E., and shown in *Fig.* 28, has been used on main road construction for slabs 8 in. and 9 in. in depth laid in alternate bays. It is reasonably cheap and easy to construct, the joints being made with pressed steel forms fixed to timber bulkheads spaced at intervals of from 10 ft. to 12 ft. As the tongues are subject to severe shearing stresses this type of joint requires great care and supervision in its construction. The minimum slab thickness for which this type of joint is suitable is 8-in.

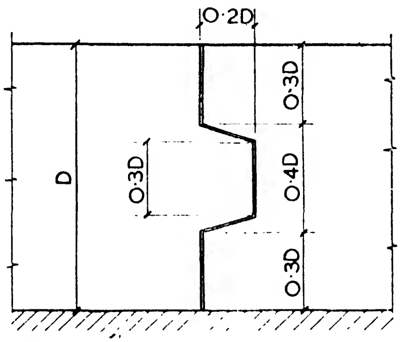


FIG. 27.—TONGUE-AND-GROOVE JOINT.

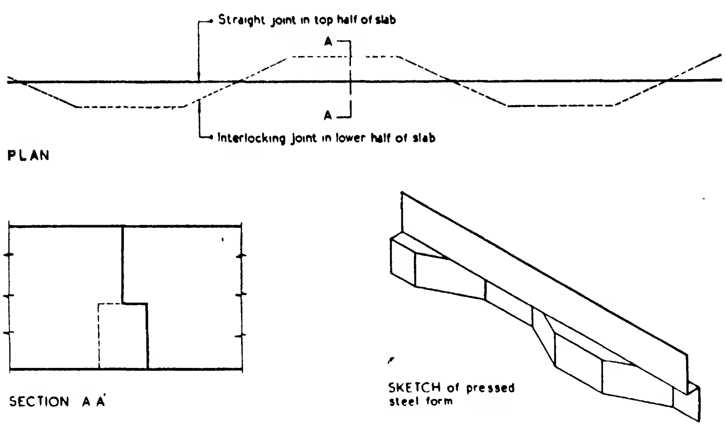


FIG. 28.—INTERLOCKING JOINT.

DUMMY JOINTS.—These joints are used to form pre-determined planes of weakness and thus control the development of cracks due to contraction. They are not efficient for the purpose of load transference from one slab to another, for aggregate interlock, as it occurs in an induced crack, breaks down after repeated loading. In order that this type of joint may control stresses caused by traffic loads it should be provided with suitable means for the purpose of load transference such as dowel plates or dowel bars. A common method of forming these joints (*Fig.* 29(*a*)) is to form a groove or channel in the slab of a depth equal to about one-third that of the slab and about one hour after the concrete has been laid. The channel should be not less than $\frac{3}{8}$ in. nor more than $\frac{3}{4}$ in. wide with edges rounded ; on completion it should be sealed with a sealing compound.

Fig. 29(*b*) shows an alternative method of forming these joints. This is satisfactory provided the timber battens are securely held in position during concreting. It has the disadvantage that the induced cracks rarely follow a straight line across the slab, but this is overcome if a cleavage line is formed for the crack to follow.

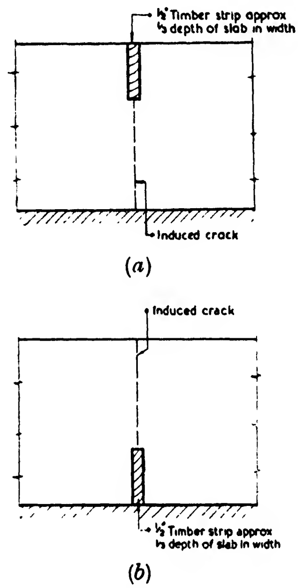


FIG. 29.—DUMMY JOINT.

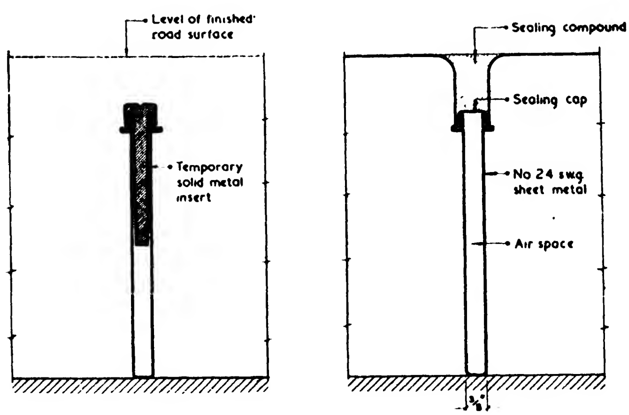


FIG. 30.—METAL CAVITY JOINT.

METAL CAVITY JOINTS.—A metal channel (about No. 30 gauge or less), ⅜ in. wide and approximately 1 in. less in depth than the thickness of the slab, is a possible solution to many of the difficulties encountered in the construction of expansion joints with premoulded or poured fillers. The metal channel (*Fig.* 30) is supported on the sub-base by temporary stakes or a metal cradle and built into the concrete, thus providing an air cavity to take up movement caused by expansion. A very desirable feature is the flange on which the jointing tool rests when the edges are rounded, this ensures that the horizontal surface of the joint is uniform throughout its length. These flanges also prevent surface water reaching the sub-base should the sealing compound be inefficient. The joint is particularly suitable for both hand and machine-compacted concrete and can be easily adapted by the manufacturers for the insertion of dowel bars by means of holes punched in the metal before it is assembled at the works.

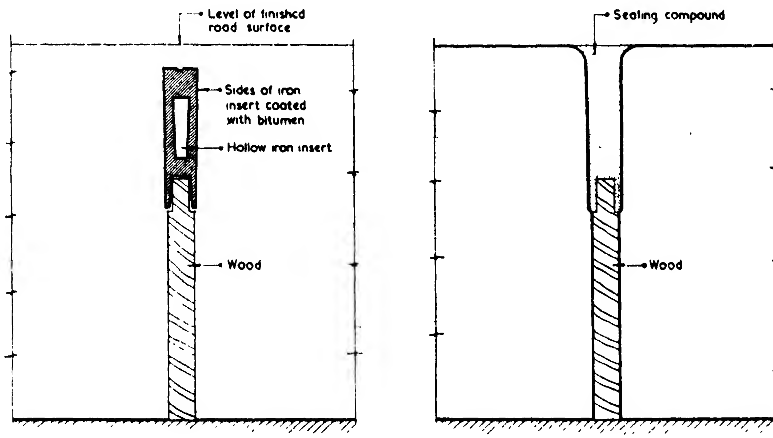


FIG. 31.—THE WIELAND JOINT.

WIELAND JOINT.—This joint (*Fig.* 31) was used extensively on the German motorways. It consists of a wooden insert on top of which rests a hollow steel section ¾ in. by 3 in. in depth, the sides of which have been coated with bitumen. The metal section is submerged about ½ in. to allow unobstructed passage of the finishing machine. About an hour after the final passage of the finishing machine the concrete covering the steel section is removed and the edges of the joint rounded. The steel section is removed a few days after by passing steam into the hollow interior; this melts the bitumen and allows the metal strip to be withdrawn for use again. The cavity is then filled with a bitumen, asbestos, or other material.

Treatment of Joints.

This is a subject to which, in the writers' opinion, sufficient attention is rarely paid. Joints in any structure are usually planes of weakness which with other structural materials require no time limit for their completion. Concrete, however, must receive its specified treatment within a limited period, and therefore it is essential that the construction of joints, an operation requiring skill and care, should only be entrusted to skilled operatives. The following are some of the principal details that require attention.

WIDTH.—The width should not exceed ½ in. A joint ½ in. wide will be at least 1¼ in. wide at the surface allowing for arrisses of ⅜-in. radius. This surface width should not be exceeded if wheel impact is to be avoided and the sealing compound maintained reasonably flush with the road surface.

EDGES.—Edges should be absolutely straight and level, and the material of which they are composed at least equal in strength to that of the slab concrete. American practice for roads constructed by mechanical methods requires the concrete within 6 in. of the joint to be given internal vibration and all loose stones removed in front of and off the joint before the final passage of the finishing machine. On no account should edges be finished with cement slurry, or water added to increase workability. The slurry often contains laitance which has little strength when hardened and the addition of water, unless lightly scattered by brush over the surface, is likely seriously to reduce the strength of the concrete at points where it is most needed.

LEVEL.—If the carriageway is to possess good riding qualities it is essential that there should be no difference in level at joints. This is only possible if the concrete surface on each side of the joint is checked for level by means of a straight-edge about 3 ft. in length as soon as the edges have been rounded and before the concrete has hardened. Badly finished edges are often due to expansion jointing material being fixed at the same or a slightly higher level than the road surface, thus preventing the uninterrupted passage of the tamper or the finishing machine over the joint. It is very necessary that this operation should be as continuous as possible, and in order to facilitate this none of the jointing material, whether of a temporary or permanent nature, should be within $\frac{3}{4}$ in. of the finished surface.

Although it is common practice in hand-compacted work to keep the filler level with, or even higher than, the finished level, this method cannot be recommended. In the first place the filler, owing to its pliable nature, buckles under pressure of the concrete and is not in true alignment; secondly, it provides unsatisfactory support for the edging tool; and, finally, if a compound is used to seal the top of the joint at least 10 per cent. of the filler has to be removed in order to make room for the sealing material. Some of these difficulties may be avoided by the use of an approved "installing bar" (see later) or some other device against which the pre-moulded filler is fastened before placing the concrete. Alternatively a metal cavity joint such as that illustrated in *Fig.* 30 should be employed since this is rigid and can be maintained in true vertical and horizontal alignment.

Expansion Joints with a Premoulded Filler.

This is probably the most common and cheapest form of expansion joint, its efficiency depending upon the care exercised in maintaining the filler in true vertical and horizontal alignment during construction. A simple device for the purpose is shown in *Fig.* 37 and consists of $\frac{3}{8}$-in. mild steel serrated plate equal in depth to the slab. The filler is placed against one side of the plate, and concrete is deposited evenly on both sides and to within about 2 in. from its top; the plate is then withdrawn and the concrete tamped evenly on both sides of the jointing material for the full depth of the slab. The serrations in the plate ensure that the concrete is maintained in close contact with the filler and also facilitate the withdrawal of the plate.

The use of mechanical plant has somewhat complicated the problems of expansion joint construction owing to the work being continuous and the tendency of concrete to " bank " or surge in front of the finishing machine if there is any vertical obstruction closer than about ¾ in. to the surface of the slab. This problem is dealt with in America by using an " installing bar " (*Fig.* 32) or device against which the premoulded filler is placed and whose top edge is uniformly ¾ in. below the proposed permanent surface. The concrete adjacent to the joint is first vibrated by vibrators inserted into the concrete by hand and worked along the entire length of the joint on both sides. After this operation is completed the finishing machine is brought forward until the front screed is approximately 8 in. from the joint, segregated aggregate is then removed from in front of and off the joint, the screed is lifted and brought directly above the joint and set upon it, and the forward motion of the finishing machine is then resumed. When the second screed is close enough to permit the excess mortar in front of it to flow over the

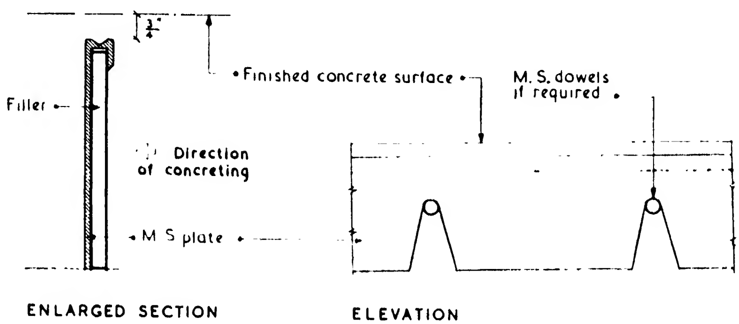


FIG. 32.—INSTALLING BAR FOR PREMOULDED FILLER.

joint it is lifted and carried over the joint. Thereafter the finishing machine may be run over the joint without lifting the screeds provided there is no segregated coarse aggregate immediately between the joint and the screed or on top of the joint. After the concrete has been finished the installing bar or channel cap (or both) is withdrawn, leaving the pre-moulded filler in place. Freshly mixed concrete is then worked into any depressions caused by the removal of the installing bar and the concrete on both sides of the joint vibrated. Immediately after these operations are completed the joint edges are rounded; the joint is not sealed until after the curing period has expired. These requirements, based on specifications for concrete road construction issued by the American Association of State Highway Officials, clearly indicate that the construction of expansion joints is one that calls for careful attention if satisfactory results are to be ensured.

CHAPTER VI

FORMWORK

The shuttering or formwork retains the concrete until it has hardened and provides supports or guides for the tools or the machines by which the concrete is consolidated and finished. The selection of forms that will provide adequate rigidity and stability, together with suitable bases on which the forms are laid, require careful consideration because on these depends the accuracy of the finished road surface. These requirements particularly apply to paving that is to be compacted and finished by machine, as the forms and the base upon which they are laid must not only take the weight of the heavy equipment but also withstand without appreciable movement varying degrees of vibration and shock.

The formation having been graded as described in Chapter II, the thickness of the concrete is determined by the height of the forms and the shape of the rule, tamper, or smoothing board. Any desired cross-fall may be obtained by using a straightedge to straddle cambered transverse forms or by a cambered rule worked normally to longitudinal side forms. These are known as longitudinal and transverse ruling respectively. In both methods the forms carrying the rule, tamper, or smoothing board must be carefully set to the longitudinal gradient by boning from adjacent level pegs.

Longitudinal tamping is customarily associated with alternate-bay construction. Its speed is limited by the length of the tamper—in practice about 15 ft. is considered a maximum. This entails the use of numerous transverse forms, each cambered to the desired cross-fall and boned in to give a uniform longitudinal gradient. This method has been satisfactorily employed. It should be observed that although longitudinal tamping is especially applicable, and has been invariably adopted where alternate-bay construction has been relied upon to meet the requirements of expansion and contraction, its use in no way precludes the provision of joints employing a pre-moulded filler.

The use of a tamping bridge (*Fig.* 33) reduces the number of transverse forms required and may be constructed so as to enable the camber to be varied from point to point along the road as may be necessary on a level site to provide channel gradients between gullies and to conform to changes in superelevation. If transverse tamping is adopted a cambered template is used and the formwork is generally simplified. The side forms are set to the longitudinal gradient. The cross forms are only needed at transverse joints to retain the concrete in position, and not to determine its surface, this being controlled by the cambered template throughout the work.

The following are the essentials of good formwork. The forms must be (1) Strong enough to withstand tamping and finishing without deformation; (2) sufficiently rigid to resist the horizontal thrust of the concrete during its consolidation; (3) durable under repeated use; (4) of a weight such that each unit can be easily handled; and (5) designed to facilitate rapid erection and removal. Adaptability for various thicknesses of concrete is a desirable feature but difficult to secure.

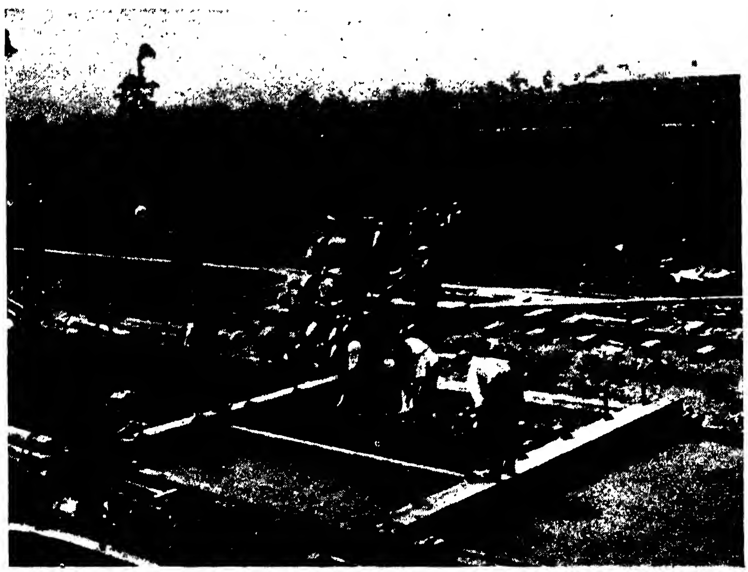


FIG. 33.—TAMPING BRIDGE.

Timber forms (*Fig.* 34) are usually made to the size required, whereas steel forms (*Fig.* 35) are generally made in standard sizes which are increased in height when necessary by placing steel or wood strips under their lower edge or by bolting two forms together one above the other. One type is readily adaptable for three different thicknesses of road and facilitates the extension of the reinforcement through longitudinal joints to connect adjacent bays. The necessity for

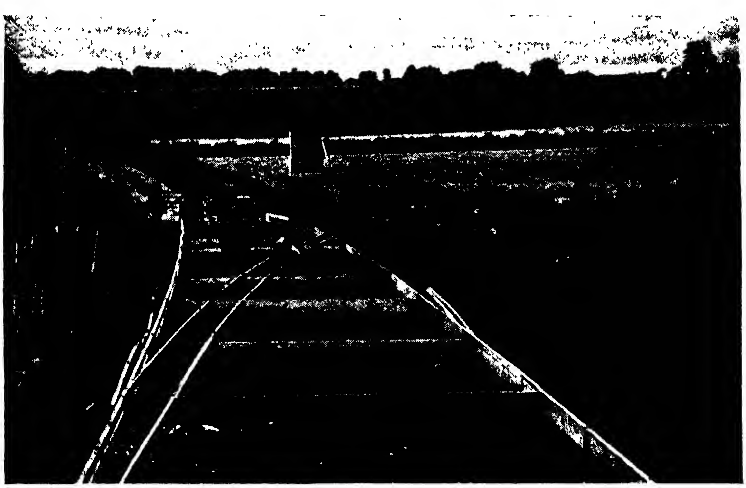


FIG. 34.—TIMBER FORMS FOR ALTERNATE-BAY CONSTRUCTION.

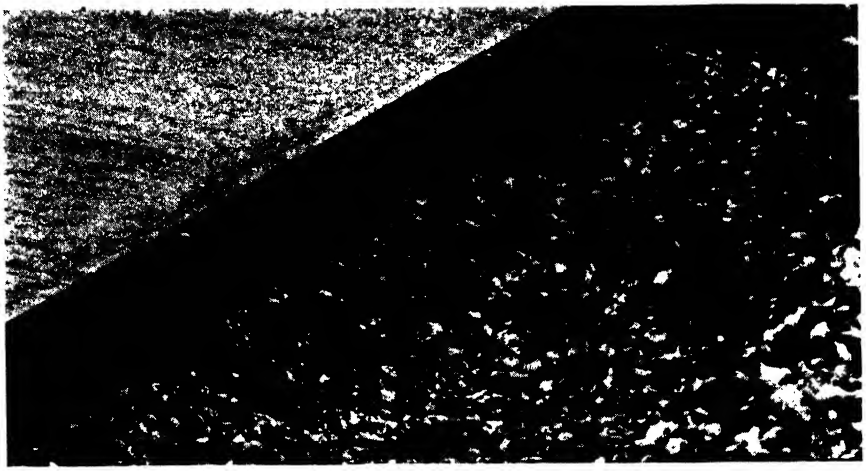


Fig. 35.—Steel Forms.

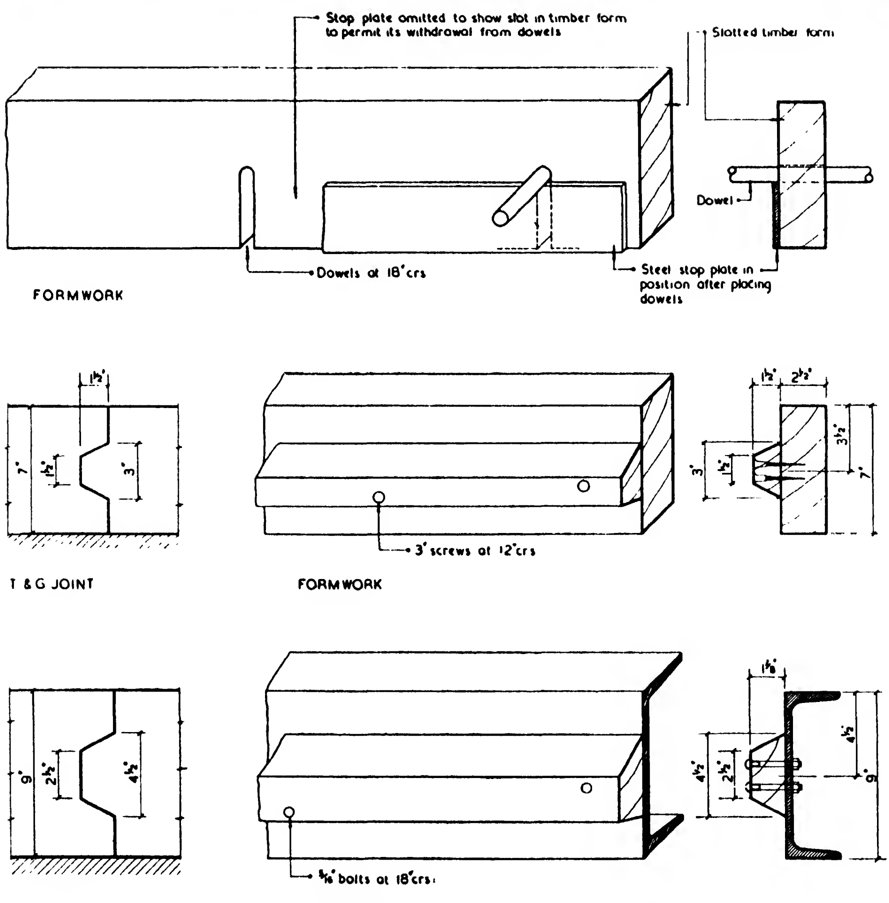


Fig. 36.—Forms for Dowelled and Interlocking Joints.

providing means of load transference at joints to meet certain conditions of traffic and foundation is becoming increasingly recognised. This subject is discussed in Chapter V. *Fig.* 36 shows the types of formwork generally adopted for the construction of dowel-bar joints and tongue-and-groove joints. The use of steel dowels across longitudinal joints requires a form provided with slots in the lower half of its vertical member, the concrete being prevented from flowing through the slots by a thin plate of metal which is not secured to but rests along the timber shutter.

The top edges of transverse forms should follow approximately the camber of the road so that slotted straightedges may be used to straddle the joint and check the surface for accuracy before the concrete sets. For this reason, and to assist in rounding the arrises at the joint, the top edge of the cross form should not be below the concrete surface and not more than ½ in. above it.

Where concreting beyond the joint is immediately proceeded with, the withdrawal of the cross form is much facilitated if its lower edge is serrated as shown in *Fig.* 37, in which the form is of ⅜-in. steel plate with a lifting eye at

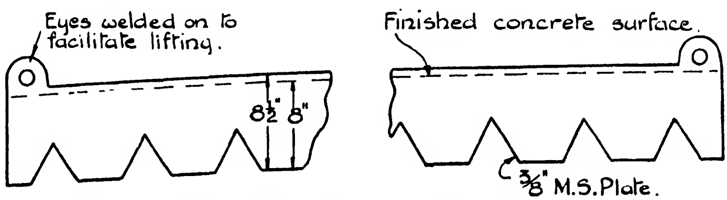


FIG. 37.—CROSS FORM SERRATED TO FACILITATE WITHDRAWAL.

each end. The serrations should be fairly deep and wide and permit a sufficient volume of concrete to come in contact with the jointing material, thus holding the latter in position at the base by pressing it against the concrete already placed. This type of form is similar to that shown in *Fig.* 38, which is serrated

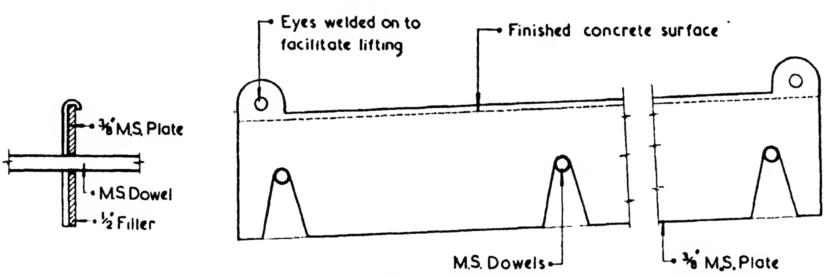


FIG. 38.—CROSS FORMS TO PERMIT USE OF DOWELS ACROSS JOINTS.

to suit the diameter and spacing of steel dowels with one end fixed and the other free in the concrete. In both cases the sheet joint filler is placed on the side of the form that is to be concreted first.

Timber Forms.

Timber forms are generally used for minor road work that is to be compacted and finished by hand, because of their low first cost and ease of delivery in suitable widths and lengths, and also on account of their adaptability to special requirements such as junctions and comparatively sharp curves. Timber forms should be cut from well-seasoned timber wrought on two sides, and should have a finished thickness of not less than one-quarter the depth of the slab so that they may withstand without deflection the lateral pressure caused by the compaction of the concrete. They must also be firmly bedded so that they will withstand without settlement repeated blows from the tamper.

The spacing of vertical supports is important and must be decided by the depth of the concrete, the thickness of the form, and to a certain extent by the nature of the foundation. Timber side forms are generally supported by stakes, or preferably by pointed metal pins ¾ in. in diameter and about 3 ft. long, spaced from 3 ft. to 4 ft. apart.

The tamping bridge already mentioned and illustrated in *Fig.* 33 consists of a pair of timber beams mounted on wheels running on the side shutters and spanning half the width of the carriageway—or on narrow roads the full width. The concrete is tamped parallel to the kerbs with a straight tamping board working on steel bearers secured to the beams, which are adjustable to give the desired camber. As the work proceeds the bridge is moved forward.

Steel Forms.

For major road work, particularly that carried out by mechanical methods, steel forms have now almost completely superseded timber. This is not only because of their longer life and the ease with which they can be fixed and removed, but also because they do not warp and are better able to withstand the impact and vibration of mechanical plant. The foundation for metal forms should be dense, hard, and level, providing them with uniform support throughout their entire length.

Metal forms are generally made of pressed steel with top and bottom flanges, the web or sides being provided with lugs at the back of the form through which metal stakes are driven. Steel forms can be obtained for slabs from 4 in. to 10 in. deep in 10-ft. lengths. A typical example is shown in *Fig.* 35. Flexible or curved metal forms are used for curves of 100-ft. radius or less.

Bedding Forms.

The base or support for the forms will be influenced by the nature of the ground, the method of compacting the concrete and, in some measure, by the size and importance of the work. For private streets and housing site roads, the forms are usually bedded on a clinker or hardcore sub-base which generally provides adequate support for hand tampers and light hand-operated vibrators. Steel forms that are required to support mechanically-operated plant, which may weigh from 4 tons upwards, should be bedded in a substantial manner. When the sub-base is strong, and not likely to be affected by periods of bad weather, steel forms may be bedded directly thereon provided they have a sufficiently wide base to distribute the load and keep alignment. They are generally secured by 1-in. diameter metal stakes driven into the sub-base, not less than three stakes being used for each 10 ft. section, one being driven at each side of every joint.

When there are doubts of the ability of the sub-base to take heavy loads it is usual to bed the forms on lean concrete about 4 in. thick, or alternatively to secure them to timber sleepers or bearers set to the required level. On new main road work it is not unusual to provide lean concrete over the whole site. If the width of this is made more than is necessary for the top concrete, then the forms can be laid on this concrete base with occasional stakes for alignment purposes and to prevent lateral displacement. A method which attained favour on the Continent was to lay a strip of concrete along the outer edges of the road to within 2 in. of the final surface, this strip being about 18 in. to 24 in. wide and about 12 in. deep. These strips were laid with a high degree of accuracy since they supported the rails on which heavy mixing and finishing plant travelled, and their level determined that of the finished roadway. On completion of the slab the rails were removed and the strips surfaced with 2 in. of bituminous material, thus making a well-defined edge to the concrete carriageway. This method is only suitable for full-width construction carried out with plant capable of distributing and compacting the concrete in one continuous width instead of comparatively narrow strips of about 11 ft. A special double edging tool (see *Fig.* 62) is used for forming the longitudinal centre joint.

CHAPTER VII

CONCRETE MATERIALS AND PROPORTIONS

Cement.

THE cements most commonly used for concrete road construction, together with the relative British Standard specifications now in force are: ordinary Portland cement (No. 12–1940), rapid-hardening Portland cement (No. 12–1940), Portland blastfurnace cement (No. 146—1932), and high-alumina cement (No. 915—1940). Owing to its relatively high cost high-alumina cement is mostly used for comparatively small areas, such as reinstatement work and repairs in busy thoroughfares where the road must be brought into use between 12 and 48 hours after completion. For other road construction where time is an important factor rapid-hardening, or high-early-strength, Portland cement is mainly used as this permits the use of the road by traffic when the concrete is about seven days old in summer and about ten days in winter, or longer in exceptionally severe weather. This is an important consideration, particularly for thoroughfares where alternative routes are not available and which may be required to carry builders' or other constructional traffic. Portland cement to which calcium chloride is added is useful in cold weather due to its quick-setting properties; the initial set takes place in 20 minutes and the final set in 40 minutes. If calcium chloride is added on the site it should be mixed with the gauging water at the rate of not more than 2 lb. of the salt to 1 cwt. of cement. Ordinary Portland and rapid-hardening Portland cements vary only in that the latter is slightly different in chemical composition and more finely ground. Portland blastfurnace cement is manufactured principally in Scotland and is seldom used in England and Wales. It is made from a mixture of Portland cement clinker and certain types of slag, and its properties are in general similar to those of Portland cement.

WHITE PORTLAND CEMENT.—In strength and other properties white Portland cement is similar to ordinary Portland cement and may be used in the same manner. To obtain the best results a careful selection should be made of the aggregates, those recommended being silica sand and crushed material, such as silica spar, Portland stone, and calcined flint. White Portland cement is widely used for the manufacture of concrete products for road work, such as kerbs, traffic lines, signposts, and lighting standards.

COLOURED PORTLAND CEMENT.—The strength of coloured Portland cement averages about 5 per cent. less than that of ordinary Portland cement, depending on the pigment. These cements are used for cycle tracks, estate roads, private streets, and for traffic lines and pedestrian crossings. It is best to use an aggregate of the hue desired in the finished concrete.

Fine Aggregate.

So long as the fine aggregate is clean, hard, and reasonably free from clay and loamy matter it should be suitable for concrete road work provided also that it does not contain an excessive amount of fine material passing a No. 100 B.S.

sieve. Sand is generally obtained from pits, rivers, lakes, sea shores, or stone crushers.

CHARACTERISTICS.—Pit sand is generally satisfactory if washed to remove loam and organic matter, such as roots. Sand from rivers and lakes is generally uniform in character and fairly well graded. Sand from the sea shore is usually much finer and should be compared with the concrete-making properties of good quality pit or river sand; such tests may reveal that the cement content will have to be increased, due to the fineness of the sand, if concrete of satisfactory strength is to be obtained.

Stone crusher screenings, provided they are not absorbent as are certain limestones and sandstone, and are reasonably free from fine dust or "flour," are satisfactory when suitably graded. Certain whinstones are unsatisfactory due to the presence of minerals that have an injurious effect on cement. Cases have arisen where laboratory tests have not fully revealed the action of these minerals, although similar material used in practice has proved unsatisfactory. Where there is doubt about the behaviour of whinstone or any other material it is advisable to make tests at the site before deciding to use the material. These tests should include the construction in the open of one or two yards of paving made with the same materials and of the same thickness as the proposed road slab. Curing should be carried out in the manner specified, and generally the test should follow the conditions likely to occur under the contract. If the whinstone dust or other material has a deleterious effect on the concrete it will be revealed fairly quickly by retarded setting, and although the degree of retardation may vary it should be possible to decide within ten days whether the concrete is likely to be satisfactory. If it is unsatisfactory the concrete will not ring when struck with a hammer; it may have a dark and damp appearance and be easily abraded, especially with the application of a little water. Under traffic such concrete will disintegrate, and if the whinstone dust or other material is particularly harmful pot-holing will develop within a few weeks.

SILT, LOAM, AND CLAY CONTENT.—A guide to the percentage of silt, clay, loam, etc., present in a sand may be obtained by making either the preliminary site test or the laboratory test described in Appendix II. In most cases the first method will give all the information necessary. An approximate field test may be carried out as follows: Half fill a cylindrical glass jar with the sand, pour in clean water until the jar is three-quarters full, shake vigorously, and allow to stand for one hour. The thickness of the silt layer should then not exceed one-seventeenth (that is 6 per cent.) that of the sand.

CLEANLINESS.—When there is doubt regarding the presence of organic impurities the test described in Appendix II should be made. The principal value of this test is to furnish a warning that further tests of the sand are necessary before it is approved for use. Excessive discoloration of the solution used in the test does not always imply that the sand is unfit for use; small particles of oil shale, for example, although causing considerable discoloration, are unlikely appreciably to affect the quality of the concrete. Again, some lake and river sands give a dark colour in this test and yet make mortar as strong as that made with the same proportion of a clean sand of similar grading. In such cases crushing tests should be made on cubes made with the sand under test and compared with tests on cubes made with sand known to be satisfactory.

Coarse Aggregate.

Since the nomenclature of rocks is an extensive one and trade applications of names are frequently at variance with geological terms, the authors have followed the classification set out in Appendix M of British Standard No. 882—1944 for " Concrete Aggregates and Building Sands from Natural Sources." The chief groups from which coarse aggregates are obtained are—

GRANITES.—These have a crystalline structure variously described as coarse, medium, or fine grain. Each has distinct features and all are free from impurities such as pyrites (FeS_2) which is detrimental to concrete. An average value of the specific gravity of the best granites is 2·7.

BASALTS.—These are very similar to dolerites, and over part of their range the two terms are synonymous. Basalts are generally distinguishable by their vesicular or cellular structure, whilst dolerites are definitely crystalline in character. The term " whinstone " is frequently used to cover any fine-grained dark-coloured rock, such as dolerite and basalt ; quartzites are not infrequently classed under whinstone. Basalts are usually tougher than granite and stand up well to steel-tyred traffic ; their suitability for concrete road construction has been well demonstrated in Scotland and Northern England. Some dolerites contain a mineral known as chlorophaeite, and several serious failures have resulted in concretes made from it. Chlorophaeite contains a readily oxidisable ferrous constituent which causes expansion and failure of the concrete, so that when dolerites are described as whinstone it is important that they should be supplied from a source which experience has shown to be satisfactory.

LIMESTONES.—These may be obtained in various degrees of hardness, varying from soft chalk and marble to very hard close-grained crystalline rock such as dolomite. They usually make a suitable aggregate provided they have a specific gravity of not less than 2·7. Limestones of low specific gravity are unsuitable for the wearing surface of a concrete road as they tend to polish under traffic and become slippery. The softer variety may be used in the bottom course of a two-course road, the wearing course being composed of harder material. The fine dust which clings to the surface of crushed limestone is particularly objectionable and may reduce the strength of the concrete by as much as 40 per cent., so that this should be removed either by washing or by mechanical extractors such as fans. The average specific gravity of dense limestones is 2·4.

GRITSTONES.—These are mainly composed of sedimentary rocks composed of quartz grains in which sandstones predominate. The more coarse-grained sandstones are called grits. Certain sandstones contain mica and should be regarded with suspicion until laboratory tests have been carried out. A simple test is to boil a few small pieces about $\frac{3}{8}$ in. and under in size and if these disintegrate the material should be rejected.

FLINT.—In this group is a variety of minerals in which probably chert, quartz, and quartzite, the common constituents of gravels, predominate. These generally have a specific gravity of 2·75, and provided they do not contain a high percentage of soft material, such as sandstone, they make an excellent concrete aggregate. Clay is often present in gravels and river ballast, either as a film enveloping the stone particles or in the form of clay lumps. In the former case the adhesion of the mortar to the stone is weakened and hardening delayed, whereas the presence of small clay particles, provided they do not exceed 1 per cent., have little or no ill effect.

ARTIFICIAL AGGREGATES.—For concrete road work, air-cooled blastfurnace slag is the only artificial aggregate used. The true specific gravity of slags varies from 3·0 to 3·1, and the minimum weight per cubic foot required by B.S. No. 1047 (1942) is 78 lb. when crushed. In many cases the use of slag as an aggregate may be worth careful consideration in view of the likely saving in cost that may be effected.

Grading of Aggregates.

Various attempts have been made from time to time to obtain by theoretical means " ideal " gradings for an aggregate. It is now well known that instead of one ideal grading there may be many that are equally suitable and that they will vary with the cement content of the mix, the nature and physical properties of the aggregate, the degree of workability required, and other causes. Other factors being equal, the strength and durability of concrete depend upon its density. The object of grading is to provide proportions of different size particles which can be compacted so that there will be a minimum of voids in the finished concrete. A grading that will ensure maximum density may yet make a harsh mixture which cannot be easily compacted, and will therefore contain an excessive proportion of voids. Provided that there is sufficient fine material present to fill the voids in the coarse aggregate, the grading of the fine material should be varied as necessary to provide the most workable mixture ; to this extent the grading of the fine material is only important in so far as it affects workability. The chief consideration is to design a mix which can be compacted to maximum density with a reasonable amount of effort rather than one that will give the minimum of voids in theory but which may be quite unworkable in practice. In considering the grading of aggregates the principal factors to be considered are (1) The proportion of cement to aggregate ; (2) The shape of the aggregate (that is, whether the particles are rounded, angular, or cubical) ; (3) The method of compaction, that is, whether by hand or machine ; and (4) The size of the largest particles.

COARSE AGGREGATE.—The limiting percentages of material passing a specified sieve given in B.S. No. 882 (1944) for various sizes of coarse aggregate are :

Passing B.S. sieve	Nominal maximum size		
	1½ in.	¾ in.	½ in.
1½ in.	Not less than 95	—	—
¾ in.	30 to 70	Not less than 95	—
½ in.	—	—	Not less than 90
⅜ in.	10 to 35	25 to 55	40 to 35
$\frac{3}{16}$ in.	Not more than 5	Not more than 10	Not more than 10

These are the limits within which a satisfactory grading is likely to be found for normal mixes, aggregates, and methods of compaction. For more detailed information reference should be made to Professor H. N. Walsh's book, " How to make Good Concrete," and to Road Research Technical Paper No. 5, "The Grading of Aggregates and Workability of Concrete," by Glanville and Collins.

FINE AGGREGATE.—Since the strength and workability of concrete are largely governed by the quantity of fine aggregate passing B.S. sieves Nos. 52 and 100, it is important that a sufficient amount of this material should be present. This particularly applies where the coarse aggregate is crushed stone or the nominal mix is leaner than 1 : 1½ : 3. For 1 : 2 : 4 mixes it may be taken as a general guide that not more than 25 per cent. and not less than 5 per cent. should pass a B.S. sieve No. 52 for a coarse aggregate of gravel, increasing the latter quantity to 10 per cent. for crushed stone. Although material finer than a B.S. sieve No. 100 may improve workability, in some cases it may require the use of more water and therefore give low strength. This is reflected in many specifications which require the fine material passing the No. 100 sieve not to exceed 3 per cent.; it is the writers' opinion, however, that in most cases 10 per cent. would be a more satisfactory limit, particularly for vibrated work, using 1½-in. aggregate. American specifications for important road schemes sometimes require 15–20 per cent. to pass a No. 50 U.S. Standard sieve and an appreciable quantity through a No 100 sieve for work that is to be vibrated. It will be noted that the following grading for fine aggregate class A (B.S. No. 882—1944) requires the higher limit for the percentage passing B.S. sieve No. 100 to be 10 per cent. for natural sand or crushed gravel sand and 15 per cent. for crushed stone sand.

B.S. sieve	Natural sand or crushed gravel sand	Crushed stone sand
	Per cent. passing	Per cent. passing
$\frac{3}{16}$-in.	95 to 100	90 to 100
No. 7	70 to 95	60 to 90
No. 14	45 to 85	40 to 80
No. 25	25 to 60	20 to 50
No. 52	5 to 30	5 to 30
No. 100	0 to 10	0 to 15

Concrete for road work must be carefully proportioned to satisfy the requirements of strength, durability, workability, and economy. Strength and durability are generally of first importance and a strong concrete is generally durable when it has hardened. For this reason crushing strength is generally accepted as the criterion of the quality of concrete. Durability depends, as do watertightness and surface finish, on density, which in turn depends upon the grading of the aggregate and the workability of the concrete when it is placed; since grading influences workability, these two factors must be considered together, and the grading altered if necessary to ensure the necessary workability to permit proper compaction.

For a given water and cement content and with the same proportions of fine and coarse aggregate, the workability of concrete depends largely on the fineness of the sand. Finer sand increases its workability and coarser sand tends to make it harsh. If there is no alternative to the coarser sand the proportions should be changed, the sand content being increased and the amount of coarse aggregate slightly decreased. The following summarises the principal considerations when deciding the proportions of concrete mixes.

(1) The workability, and consequently the strength and economy, of concrete mixes of nominal proportions 1 : 2 : 4 are largely governed by the amount of sand passing B.S. sieves Nos. 52 and 100. It may be taken as a guide that the proportion of this fine material in sand should range from 5 per cent. in rich mixes to 30 per cent. in 1 : 2 : 4 and leaner mixes.

(2) As the maximum size of coarse aggregate is decreased the sand content should be increased. For example, if the maximum size of the coarse aggregate is 1½ in. for a nominal 1 : 2 : 4 mix and the material is reasonably well graded, the sand content, assuming it is dry and that no correction is necessary for bulking, may be reduced to give proportions of 1 : 1½ : 4½, while for similar material of ¾ in. maximum size the most suitable proportions are likely to be 1 : 2 : 4. Suitable proportions if the maximum size of the aggregate is, say, ⅜ in. would be 1 : 2 : 3. These three mixes should give concretes of about the same strength and workability with a given water-cement ratio.

(3) The sand content should be increased if the degree of workability requires to be increased. Lack of workability generally arises owing to lack of cement-sand mortar to fill the spaces between the particles of large aggregate ; this can generally be corrected by the addition of a small proportion of sand or the use of a finer sand ; if more sand is added the proportion of coarse aggregate must be reduced to maintain the specified ratio of cement to aggregates.

"ALL-IN" BALLAST AND "ALL-IN" CRUSHED STONE.—The sieve analysis for this material given in B.S. No. 882—1944 is given below. The specification requires material between the maximum and minimum sizes to be well graded and to include an adequate percentage of all intermediate particles.

B.S. sieve	Nominal maximum size	
	1½ in.	¾ in.
	Per cent. passing	
1½-in.	95 to 100	—
¾-in.	40 to 70	95 to 100
$\frac{3}{16}$-in.	25 to 45	30 to 50
No. 100	0 to 6	0 to 6

GRADING FOR MACHINE-COMPACTED CONCRETE.—The grading of the fine and coarse aggregates for slabs that are to be compacted by machine will differ from that required for work to be compacted by hand. Since stiffer mixes can be used for vibrated work, fine aggregate that is coarsely graded is generally satisfactory for use with crushed or uncrushed coarse aggregate, provided that there is sufficient fine material to fill the voids ; the water content, however, may require slight adjustment, possibly an increase of about 2 per cent. Typical gradings for machine-compacted concrete used for important road work constructed in this country and abroad, together with typical gradings adopted for large-scale experimental work undertaken in America to study the effect of vibration on the strength and uniformity of concrete paving, are given later in this chapter.

Proportioning.

Many methods of proportioning concrete have been devised from time to time. It is not possible here to deal with all of them; the following, however, are those most commonly used for road work and which experience has shown to give satisfactory results.

PROPORTIONING BY ARBITRARY METHODS.—This is probably the oldest and best known method in which the relative amounts of cement, sand, and stone are selected. Those most commonly used for concrete road work are 1 : 1½ : 3, 1 : 2 : 4, and 1 : 2½ : 5; in each case the volume of sand is half that of the coarse aggregate. There is no necessity to adhere strictly to these proportions, and variations are generally allowed provided that the proportion of cement to combined aggregate is not changed. As a rule it will be found that the ratio of coarse to fine aggregate lies within the limits of 1 to 1½ and 1 to 2½, depending upon the size and grading of the stone. Furthermore, these proportions are invariably based on the volume of dry materials, no allowance being made for the bulking of the sand due to moisture. If the sand, therefore, is bulked by, say, 20 per cent., the apparent sand content must be increased to allow for this, in which case the nominal proportions by volume become 1 : 1$\frac{4}{5}$: 3, 1 : 2$\frac{2}{5}$: 4 and 1 : 3 : 5.

When the measurement of aggregate is by volume and not by weight, it is preferable to specify the proportion of cement to combined aggregate, the most suitable proportions being judged by two or three trial batches before the final selection is made. *Table* XII (based on Professor Walsh's work) gives the approximate volumes of combined aggregate to a unit volume of cement for various mixes, assuming well graded material containing between 30 per cent. and 40 per cent. of dry sand.

TABLE XII.—VOLUMES OF MATERIALS FOR DIFFERENT PROPORTIONS.

Nominal proportions	Cubic feet of dry mixed aggregate to 1 cu. ft. of cement	Cubic feet of dry mixed aggregate to 1 cwt. of cement	Gallons of water per cwt. of cement
1 : 1½ : 3	4·0	5·0	5¾ to 6½
1 : 2 : 4	5·0	6·25	7 to 8½
1 : 2½ : 5	6·2	7·75	8½ to 10½
1 : 3 : 6	7·6	9·50	10 to 13

The sum of the volumes of sand and coarse aggregate in nominal mixes is greater than the combined volumes given in the second column, the reason being that when the sand and stone are first measured separately and then combined about 40 per cent. of the sand is absorbed by the voids in the stone, thus reducing the total volume. Column 4 gives water contents that produce workable mixes.

A 1 : 1½ : 3 mix is generally used where high strength and resistance to abrasion from steel tyred or heavy continuous traffic is required. It is frequently adopted for the wearing surface of two-course construction in districts where the local aggregate is not sufficiently durable to withstand hard wear, although it may be quite suitable for the bottom course. In such cases stone having high abrasive qualities is used for the top course.

A 1 : 2 : 4 mix is more commonly used than any other and, provided the aggregates are well graded and proportioned and mixed with just sufficient water to yield a workable concrete, satisfactory results can generally be obtained.

A 1 : 2½ : 5 mix is mostly used for the bottom course of road slabs laid in two courses. It is frequently adopted for mixes that are compacted and finished by mechanical means owing to the reduction in water content, and therefore increase in strength, which is possible with this method.

A 1 : 3 : 6 mix is generally specified for concrete haunching and foundations for bituminous and asphaltic surfacings for secondary roads, and as a substitute for hardcore or for pitched foundations.

PROPORTIONING BY WATER-CEMENT RATIO.—This method of proportioning is based on the fact that for given materials and conditions the quantity of mixing water used determines the strength of the concrete, provided the concrete can be fully compacted. In other words, so long as the amount of water free to combine with the cement bears a constant ratio to the amount of cement, the strength of the concrete at a given age is fixed regardless of the quantity of aggregate added so long as all the other factors are the same.

The water-cement ratio should be chosen to give the required durability, strength, and workability. Workability is important and must be studied in conjunction with the method of compaction to be applied, for example, whether this is to be by hand or by machine. The water-cement ratio for the required strength should be determined by laboratory tests to establish the physical properties of the materials to be used, variations in workability, suitable water contents, and cement requirements for various aggregate gradings and proportions. When it is not practicable to make such tests, the water-cement ratio required for a required compressive strength may be taken from *Table* XIII, which gives a number of conservative values derived from tests for which typical aggregates mixed with ordinary Portland cement were used. It must, of course, be remembered that the strengths given in the table assume that sound materials are used, and that the grading, proportioning, workmanship and curing are reasonably good.

TABLE XIII.—STRENGTHS WITH DIFFERENT WATER-CEMENT RATIOS.

Water-cement ratio (by weight)	Gallons of water per cwt. of cement (including free moisture in aggregates)	Estimated compressive strength at 28 days, using ordinary Portland cement (lb. per sq. in.)
0·45	5	5000
0·49	5½	4500
0·53	6	4000
0·58	6½	3600
0·62	7	3200
0·67	7½	2800
0·71	8	2500
0·76	8½	2000

PROPORTIONING BY FINENESS MODULUS.—The term "fineness modulus" is used in America in connection with the grading of an aggregate as determined by sieve analysis. The United States standard sieves used for this purpose are numbers 100, 50, 30, 16, 8, 4, $\frac{3}{8}$ in., $\frac{3}{4}$ in., and $1\frac{1}{2}$ in., each having a linear opening twice the size of the preceding sieve. (Note that the corresponding B.S. sieves are Nos. 100, 52, 25, 14, 7, $\frac{3}{16}$ in., $\frac{3}{8}$ in., $\frac{3}{4}$ in., and $1\frac{1}{2}$ in.) The fineness modulus is the sum of the percentages by weight of the amounts coarser than each sieve divided by 100. The practical limits of the fineness modulus for fine aggregates are from 2 to 3·5, for coarse aggregates from 5·5 to 8, and for mixed aggregates from 4 to 7. This method of proportioning, coupled with the use of the water-cement ratio, gives satisfactory results and enables the engineer to specify a fineness modulus without stating exact requirements of grading. Some contractors prefer this method because of the alternative gradings that are possible to comply with the specified modulus.

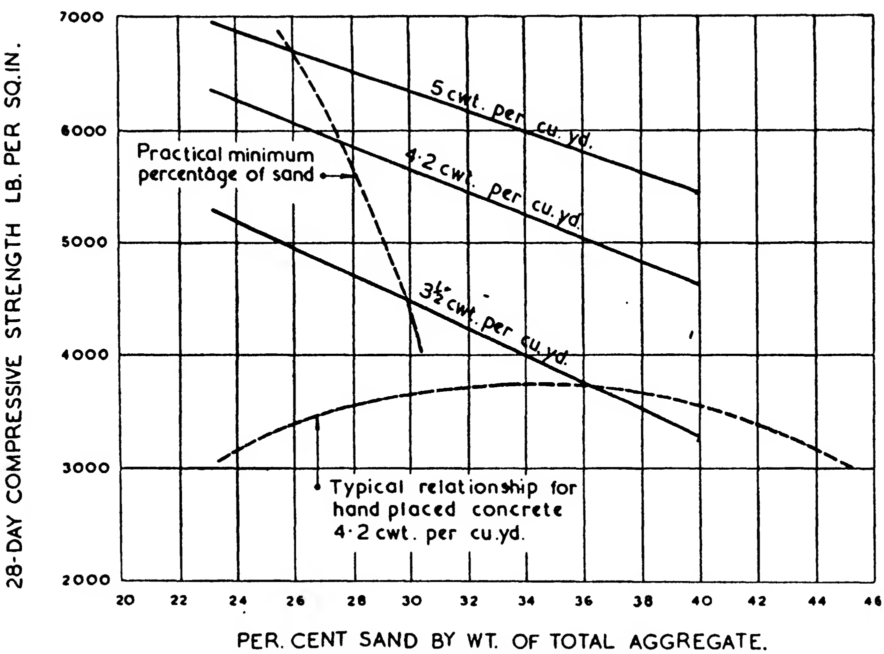


Fig. 39.—Relation between Sand Content and Strength of Vibrated Concrete.

Proportions for Machine-Compacted Concrete.—The selection of suitable proportions for concrete to be compacted and finished by vibration presents a somewhat different problem from that which arises for concrete that is compacted and finished by hand. In both cases density is an essential property, but whereas workability is the principal consideration for hand methods it is less important for machine-compacted work which permits much stiffer mixes to be used. For concrete that is to be consolidated by machine it is possible to use mixtures containing less fine material than would be required for hand-compacted work where a harsh mix is difficult to consolidate; therefore a larger proportion of coarse and a smaller proportion of fine aggregate can be used for work compacted by machine. Since coarser gradings present less surface area to be coated with cement paste, less water can be used for a given consistency;

thus improvements in quality or economy may be obtained by harsher as well as by stiffer mixes. *Fig.* 39 shows the relation between compressive strength and percentage of sand for vibrated concrete. For concrete containing 4·2 cwt. of cement per cubic yard a sand content of about 36 per cent. by weight gives the best workability for hand-placed work, but, using the same materials and cement content, the sand could be reduced to 28 per cent. by weight for vibrated work.

Mixes that are to be vibrated should be designed in accordance with one of the recognised methods suitable for hand-compacted work, that is, the water-cement ratio should be selected to meet requirements of strength and the most suitable proportions determined by trial mixes. The mixture, however, must become readily plastic under vibratory action ; variables such as the type and power of the vibrating machine and the physical characteristics of the aggregates require consideration, as these may also affect the proportions.

On page 70 are given some typical proportions for machine-compacted concrete used for road work in this country and abroad ; the English roads were in an excellent condition when they were inspected recently by one of the authors. As a matter of interest a few mixes are included that were satisfactory for large-scale experimental road work carried out with different vibrating equipment in America during 1934 by the Bureau of Public Roads.

In the following and on page 71 are typical sieve analyses, weights, fineness moduli, etc., of the materials used for some of these works.

Crawley by-pass :

	Per cent.
Passing 1½ in. but retained on ¾ in.	27·5
,, ¾ in. ,, ,, ,, ⅜ in.	17·5
,, ⅜ in. ,, ,, ,, 3/16 in.	15·0
,, 3/16 in. ,, ,, ,, No. 7	12·5
,, No. 7 ,, ,, ,, No. 14	12·5
,, No. 14 ,, ,, ,, No. 25	7·0
,, No. 25 ,, ,, ,, No. 52	6·6
,, No. 52	2·0

Winchester by-pass.—Mixed aggregates were used with four gradings conforming to the following limits :

B.S. sieve	Per cent. finer
1½ in.	87 to 100
¾ ,,	58 to 75
⅜ ,,	36 to 45
3/16 ,,	28 to 35
No. 7	25 to 28
No. 14	19 to 24
No. 25	14 to 21
No. 52	5
No. 100	2

Fineness modulus, 5·80

With the exception of one mile constructed with a Jaegar tamping machine the paving was hand compacted and finished.

Road and when built	Finishing machine	Proportions			Water-cement ratio
		Cement (lb.)	Sand (lb.)	Stone (lb.)	
Crawley by-pass (W. Sussex C.C.) 1938–1939	Aveling & Barford and Stothert & Pitt	112	224	448 (Crushed stone, 1½ in. max.)	0·44
Chichester by-pass (W. Sussex C.C.) 1938–1939	Allam Vibro-finisher in conjunction with a Stothert & Pitt distributor	Bottom Course 112	305	520 (Gravel, 1 in. max.)	0·50
		Top Course 112	220	374 (Granite, ⅝ in. max.)	0·45
Mickleham by-pass (Surrey C.C.) 1937–1938	Fraser & Chalmers' tamping and finishing machine (Dingler design)	112	320	480 (Gravel, 1½ in. max.)	0·42 to 0·51 (av. 0·45)
Winchester by-pass (Hants C.C.) (1938)	—	112	—	662 combined aggregate	0·48
German motorways 1933–1939	Dingler and Vogele	112	283	390 (Crushed stone, 1¼ in. max.)	0·40 to 0·46
Pennsylvania Turnpike, U.S.A. 1940	Jaeger, Blaw-Knox, and others	94	176	338 (Crushed stone, 2½ in. max.)	0·48 max.
Tests on the effect of vibration carried out by the U.S. Bureau of Public Roads	Jaeger "Lakewood" and Blaw-Knox machines, and a hand-operated vibrator	94	176	354 (Gravel, 1½ in. max.)	0·46
		94	209	443 (Crushed stone, 1½ in. max.)	0·50
		94	209	417 (Crushed stone, 1½ in. max.)	0·48

Road	Sand		Per cent. by weight (dry)	Gravel		Per cent. by weight (dry)	Broken stone		Per cent. by weight (dry)
Chichester by-pass	Retained on $\frac{3}{16}$ in.		0·88				Retained on $\frac{5}{8}$ in.		3·04
	Passing—	Retained on—		Passing—	Retained on—		Passing—	Retained on—	
	$\frac{3}{16}$ in.	No. 7	3·74	$1\frac{1}{2}$ in.	$\frac{3}{4}$ in.	7·94	$\frac{5}{8}$ in.	$\frac{1}{2}$ in.	13·65
	No. 7	No. 14	8·95	$\frac{3}{4}$,,	$\frac{1}{2}$,,	34·25	$\frac{1}{2}$,,	$\frac{3}{8}$,,	37·59
	No. 14	No. 25	25·45	$\frac{1}{2}$,,	$\frac{3}{8}$,,	23·34	$\frac{3}{8}$,,	$\frac{1}{4}$,,	29·56
	No. 25	No. 52	45·23	$\frac{3}{8}$,,	$\frac{1}{4}$,,	21·58	$\frac{1}{4}$,,	$\frac{3}{16}$,,	8·58
	No. 52	No. 100	13·25	$\frac{1}{4}$,,	$\frac{3}{16}$,,	5·95	$\frac{3}{16}$,,		7·57
	No. 100		2·46	$\frac{3}{16}$,,		6·94			
Mickleham by-pass	Retained on $\frac{3}{16}$ in.		0·00						
	Passing—	Retained on—		Passing—	Retained on—				
	$\frac{3}{16}$ in.	No. 7	3·3	$\frac{3}{4}$ in.	$\frac{3}{8}$ in.	75·1			
	No. 7	No. 14	15·2	$\frac{3}{8}$,,	$\frac{3}{16}$,,	22·0			
	No. 14	No. 25	39·0	$\frac{3}{16}$,,		2·9			
	No. 25	No. 52	34·0	Fineness modulus		6·72			
	No. 52	No. 100	7·7	Voids		44·5			
	No. 100		0·8	Weight per cubic foot (dry)		95 lb.			
	Fineness modulus		2·59						
	Voids		31·4						
	Silt		4·2						
	Weight per cubic foot (dry)		107·5 lb.						

Pennsylvania Turnpike.—The gravel was divided into two sizes, A and B, and proportions adjusted to give the desired workability:

Sieve size	Per cent. passing square U.S. sieves		
	Sand	Stone	
		Size A	Size B
$2\frac{1}{2}$ in.		100	
2 in.		90 to 100	
$1\frac{1}{2}$ in.		35 to 70	100
1 in.		0 to 15	90 to 100
$\frac{1}{2}$ in.			25 to 60
No. 4	95 to 100		0 to 10
No. 16	45 to 80		
No. 50	10 to 30		
No. 100	0 to 8		

German Motorways.—A typical grading used on the German motorways is as follows:

mm.	ins.	lb.
0–3	$0-\frac{1}{8}$	1350
3–5	$\frac{1}{8}-\frac{3}{16}$	316
3–5	$\frac{1}{8}-\frac{3}{16}$	158
5–8	$\frac{3}{16}-\frac{6}{16}$	396
8–12	$\frac{5}{16}-\frac{1}{2}$	396
12–18	$\frac{1}{2}-\frac{3}{4}$	396
18–30	$\frac{3}{4}-1\frac{3}{4}$	950
Cement		660

Water-cement ratio by weight, 0·46

CHAPTER VIII

MIXING, PLACING, AND FINISHING CONCRETE

THE materials must be correctly proportioned and measured if strength, durability, workability, and economy are to be fully developed. This is particularly necessary in the case of road work, which is subject to extremes of temperature and moisture and must also withstand severe stresses arising from the impact and vibration of traffic. Unless the variations that can result from measurement in gauge boxes are fully appreciated the yield of concrete as well as its quality may be influenced considerably.

CEMENT.—The best way of measuring cement is by weight, either by using a scale or by using the 112-lb. bag as the unit for each batch. Normally, cement is assumed to weigh 90 lb. per cubic foot. Measured by loose volume it may weigh from 75 lb. to 90 lb. per cubic foot or even more, depending upon the method of filling the gauge box. The 112-lb. bag is considered in the Code of Practice as equal to 1¼ cu. ft., although if shovelled from the bag into the gauge box it may occupy a volume approaching 1½ cu. ft. With mixers of certain capacities it is not possible to use one or more bags for each batch. If a bag has to be divided accuracy can be ensured by weighing the odd amount into a bucket suspended from a 100-lb. spring balance.

FINE AGGREGATE.—When fine aggregate is measured by volume serious discrepancies may occur in the actual quantity of sand used owing to the phenomenon known as bulking. Whether dry or saturated, sand occupies the same volume, but in any intermediate stage of moisture content the volume is increased. The following table shows the amount of bulking in the case of various sands loosely filled into a container as determined by Professor Walsh and Dr. Glanville.

Percentage water content by weight of dry sand	Bulking of sand. Percentage of dry volume		
	Professor Walsh		Dr. Glanville
	Coarse sand	Fine sand	River sand
0	0	0	0
1	5	4	16
2	10	10	24
3	17	18	26
4	23	23	26
5	25	27	24
10	21	35	16
15	2	15	10
20	0	0	3

The following table shows the grading of the coarse and fine sands examined by Professor Walsh (see his book "How to Make Good Concrete") included in the foregoing table.

F

	B.S. sieves						
	No. 100	No. 52	No. 25	No. 14	No. 7	$\frac{3}{16}$ in.	$\frac{3}{8}$ in.
Fine sand, per cent. passing .	9	24	47	65	84	98	100
Coarse " " " " .	0·4	2·5	14·2	43·3	80·7	100	100

With an average moisture content sand bulks about 20 per cent. of its volume, so that if 2½ cu. ft. of sand are specified and no allowance is made for bulking, the quantity of sand that should be measured into the gauge box will be 1·2 × 2½ cu. ft. = 3 cu. ft. An apparatus is available, which is convenient and simple to use, which enables the user to determine quickly and easily the extra volume of damp sand which should be used in order to give the amount of actual sand required. From the contractor's point of view proper allowance should be made for the bulking of sand because it increases the yield of concrete per bag of cement and therefore reduces the unit cost of the concrete. It is important

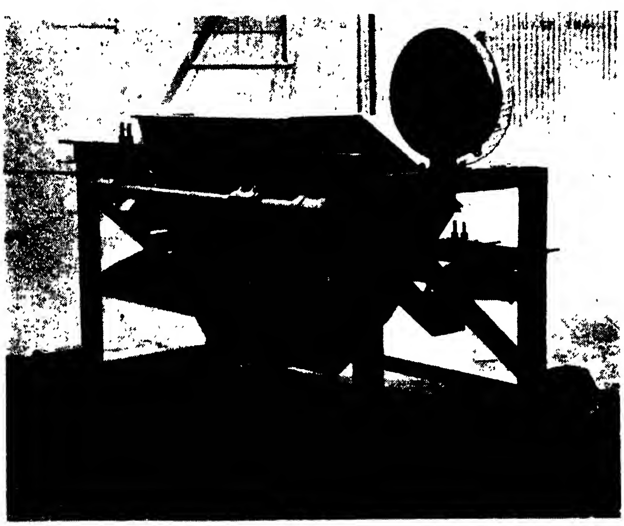


FIG. 40.—MACHINE FOR MEASURING MATERIALS BY WEIGHT.

from the engineer's point of view because the workability of the concrete is increased, thus providing easier compaction which in turn results in greater density and strength.

The effect of sand bulking need not be considered when mixes are proportioned by weight, because, as is seen from the table, in the worst condition of bulking, the water content is only about 5 per cent. of the total weight. Formerly measurement by weight was only practicable on work sufficiently large in magnitude to bear the cost of the necessary batching plant. However, it is now possible to obtain portable batch weighers for use with mixers of as small capacity as 7/5 cu. ft. (*Figs.* 40 and 41).

COARSE AGGREGATE.—Coarse aggregate can be measured by either weight or volume since with the normal types of aggregate used for road work no bulking occurs. Allowance must, however, be made for the quantity of free moisture contained in both the fine and coarse aggregates; this is particularly important if the water-cement ratio of the mix is specified (see later).

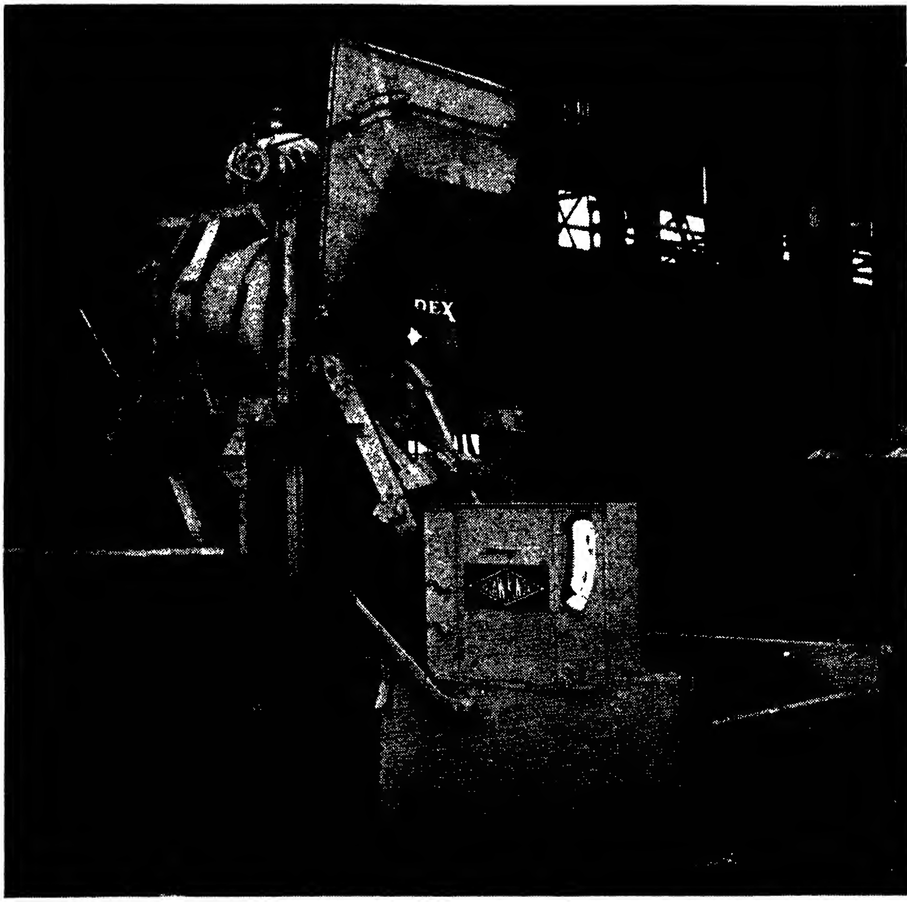


FIG. 41.—WEIGH-BATCHING PLANT.

WATER.—Mixing water is generally measured by means of a tank mounted on the mixer and fitted with a measuring device, which for work of any magnitude is required to be accurate to 0·5 per cent. On many American machines the water-measuring device is in a case which can be kept locked, the controls being so arranged that the flow of water can be started only while the mixer is being charged.

The total water in the batch will comprise the water added plus the water carried by the aggregates. Since all aggregates as used in practice contain moisture which becomes part of the mixing water, this must be determined to arrive at the exact amount to be added from the tank. The amount of free, or surface, water carried by aggregates is approximately as follows: Very wet sand, $\frac{1}{2}$ to $\frac{3}{4}$ gallon per cubic foot; moderately wet sand, $\frac{1}{2}$ gallon; moist sand, moist gravel, and crushed stone, $\frac{1}{4}$ gallon. The coarser the aggregate the less free water it will carry. Assuming that the coarse aggregate contains $2\frac{1}{2}$ lb. of free moisture per cubic foot, then the amount of water to be added if the specified water content is $6\frac{3}{4}$ gallons per bag of cement for a mix containing 3 cu. ft. of moderately wet sand and 5 cu. ft. of coarse aggregate is

			lb.
Free moisture in 3 cu. ft. of sand		$= 3 \times 5$	$= 15$
,, ,, ,, 5 cu. ft. of coarse aggregate		$= 5 \times 2\frac{1}{2}$	$= 12\frac{1}{2}$
			$27\frac{1}{2} = 2\frac{3}{4}$ gallons.

Therefore the quantity of water to be added is $6\frac{3}{4} - 2\frac{3}{4} = 4$ gallons.

Dry aggregate will absorb moisture, and this absorbed water will reduce the amount available as gauging water. But as this absorption never exceeds 1 per cent. by weight of the aggregate, and as aggregates are seldom if ever received at the mixer in a bone-dry condition, this may be ignored.

Mixing.

Economy as well as uniform quality require machine-mixed concrete for road work. Nevertheless it is recommended that provision be made for hand-mixing. Since, in order to make it sufficiently workable to ensure proper mixing at economical cost, hand-mixed concrete requires about 30 per cent. more water than that mixed by machine, it is necessary to increase the cement content by 30 per cent. if the same strength is to result. However, hand-mixing is as a rule adopted for work of minor importance only, and it is sufficient to add about 10 per cent. more cement to compensate for the loss in strength due to the increased water content.

Concrete for road work is generally mixed by power-operated batch mixers. These mixers are of two types, (*a*) closed or fixed drum and (*b*) tilting drum. In the closed or fixed-drum machine the mixing drum is rotated on a horizontal axis, the concrete being thrown against blades projecting at an angle to the periphery of the drum to which they are fixed and so arranged that as the drum revolves the concrete is gradually worked to the front of the mixer. Discharge of the concrete is by means of a mechanically-operated steel chute inserted into an opening in the face of the drum. *Fig.* 42 shows mixers of the closed-drum type in use on work of considerable magnitude.

Tilting-drum machines are rotated through an angle of about 180 deg. and are loaded with the mixing drum in a horizontal position. These machines are mostly used for minor road work, requiring a comparatively small amount of concrete.

The foregoing remarks refer to batch mixers which are in general use since they permit the cement and aggregates to be mixed in batches of a predetermined volume or weight. Progress has recently been made with the "continuous" type of mixer in which the cement and aggregates are supplied unmeasured into separate hoppers and thence proceed by means of suitably geared conveyors into one or more mixing drums which provide a constant outflow of mixed concrete.

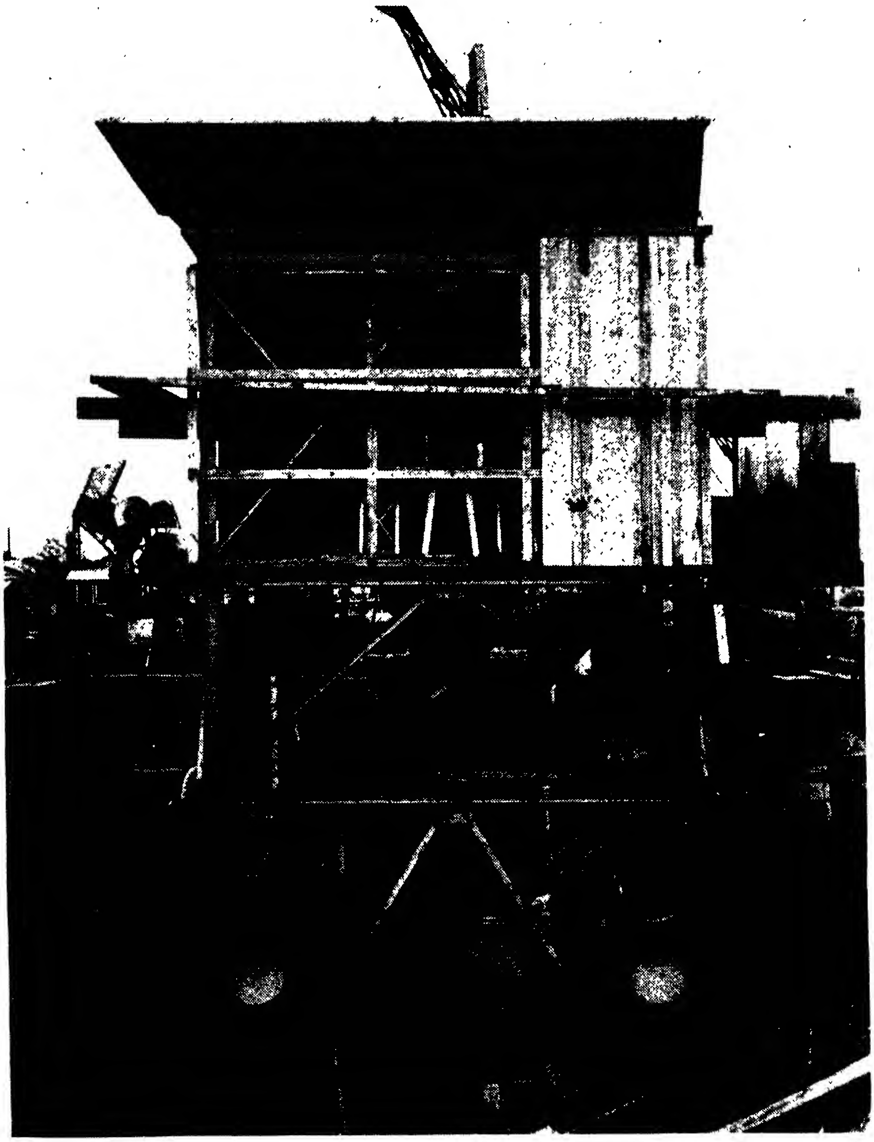


FIG. 42.—WEIGH-BATCHING PLANT AND CLOSED-DRUM MIXERS.

The relative proportions of the mix and the rate of output depend upon the size and speed of the conveyors ; the speed is adjustable by variation of the gearing. The water, which is adjusted by a valve, is generally passed with the cement into a separate mixing compartment before they are added to the aggregates in the main drum. These mixers give economical results where a considerable output is required and the supply of materials is well organised.

A new attachment designed to control the time the materials are in the mixer drum is a device incorporating an escapement operated by a weight which can be set for any desired mixing period and which, at the end of that period, rings a bell and simultaneously unlocks the hand lever operating the discharge mechanism. Another device enables the operator to adjust the quantity of water to give the required consistency, and automatically registers the quantity used with each mix and also the mixing time. It further shows the periods during which the plant is working or standing idle, and thus provides a record of the output of the mixer.

MIXING TIME.—The period of mixing has an important influence upon the strength, uniformity, and workability of concrete. Concrete mixed for only 15 seconds may have a variation of about 30 per cent. of the average strength, particularly in the case of stiff mixes, whereas concretes mixed for two minutes usually vary less than 10 per cent. With up-to-date mixers the concrete should be mixed for 1½ minutes after all the materials have been loaded into the drum. Machine mixing for periods in excess of two minutes does not add materially to the strength of the concrete and is not economical.

TABLE XIV.—INFLUENCE ON OUTPUT OF SIZE OF MIXER AND PERIOD OF MIXING.

Mixing time (minutes)	Total charging and discharging time (seconds)	Capacity of mixer in cubic feet of mixed concrete							
		5	7	10	14	20	27	34	34 Dual drum
		Approximate cubic yards per hour							
1	15	8¾	12½	17¾	25	35½	48	60	121
1¼	15	7½	10½	14¾	20¾	29½	40	50	100
1½	15	6¼	9½	12½	19	25	34¼	43	86
1	20	8¼	12	16½	24	33	45	57	113
1¼	20	7	10	14	20	28	38	47¾	95
1½	20	6	8½	12	17	24	33	41	82
1	30	7½	10½	14¾	20¾	29½	40	50	100
1¼	30	6¼	9½	12½	19	25	34¼	43	86
1½	30	5½	7¾	11	15½	22	30	38	76

Indifferent mixing results if the mixer is overloaded or if the interior of the drum is not kept clean. These factors have a far greater effect upon the concrete than a slight variation in the rate of rotation of the drum. If a properly-operated machine cannot keep pace with the concretors the remedy is a larger mixer, but as the charging and discharging operations and mixing times are very important if maximum output is to be obtained, these items should be carefully studied before making a change. For example, suppose that a batch mixer is used having a capacity of 27 cu. ft. of mixed concrete and the time occupied in charging and discharging the drum occupies 30 seconds. With a mixing time of one minute the output per hour will be 40 cu. yd. If, however, the charging and discharging cycle is reduced to 15 seconds the output will be 48 cu. yd. per hour, an increase of 20 per cent. *Table* XIV illustrates the relative outputs of several sizes of mixer for mixing periods of from 1 minute to 1½ minutes and charging and discharging cycles of from 15 to 30 seconds. Prolonged mixing tends to stiffen the concrete considerably, and a similar action takes place if mixed concrete is allowed to stand for long periods, the reason being that some of the mixing water combines with the cement and some is lost by evaporation, particularly in warm weather. *Fig.* 43 shows typical relationships between times of mixing and the compressive strength of concrete.

Capacity of Mixers.—The capacity of a mixer should be such as will produce

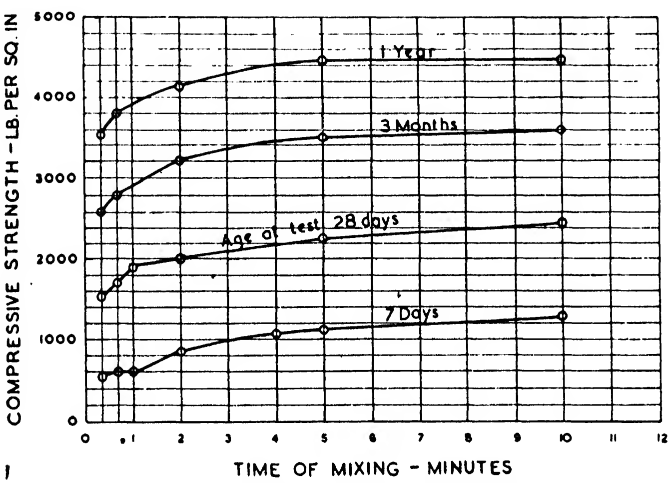


Fig. 43.—Relation between Time of Mixing and Strength of Concrete.

the required volume of concrete in a given time without reducing the mixing period below that specified. The capacity is usually indicated by the quantities in cubic feet of the unmixed and mixed materials it is designed to handle, for example 10/7 denotes a mixer capable of receiving 10 cu. ft. of unmixed material

Table XV.—Quantities of Materials Required for Various Batches.

Nominal mix	Total volume in cubic feet of cement, sand, and stone (assuming damp sand 20 per cent. bulked)		Suitable size mixer for 1 bag (112 lb.) batch
	Gravel	Broken stone	
1 : 1 : 2	5·00	5·25	7/5
1 : 1½ : 2	5·62	6·00	7/5
1 : 1½ : 3	6·87	7·24	7/5
1 : 2 : 4	8·75	9·25	10/7
1 : 2½ : 4	9·37	10·00	10/7
1 : 3 : 5	11·25	12·00	14/10
1 : 3 : 6	12·50	13·25	14/10
1 : 4 : 8	16·25	17·25	22/14

and producing 7 cu. ft. of concrete. The 10/7 machine is the smallest size generally used on road work. *Table* XV gives the quantity of materials required for a 1-bag batch of different proportions.

When selecting a mixer the following points should be considered: (*a*) thorough mixing without segregation; (*b*) robust construction, simplicity of design and operation together with accessibility for cleaning, lubricating, and repairing; (*c*) adequate power for charging, mixing, and discharging; (*d*) adequate water supply, with simple and accurate means of measurement; (*e*) sufficient capacity for size of batch required, to avoid spilling and waste; (*f*) rapid and complete discharge of the loading hopper and of the mixed concrete without recourse to hammering or other means.

FIG. 44.—TRUCK FOR TRANSPORTING CONCRETE.

Transporting Concrete.

The conveyance of concrete to the site, its placing, and its distribution are so closely related that they must be studied separately and then co-ordinated. It is obviously uneconomical to transport concrete long distances if sufficient space for the storage of materials and the mixing plant is available adjacent to the site. Neither is it sound practice to place a large volume of concrete on the sub-base and require it to be spread by hand. It is impossible to lay down any hard and fast rule on the best method to adopt for these operations, which are influenced by such factors as access to the site, the type and capacity of the mixing plant, the daily requirements of cement and aggregates, and, in some districts, water supply. In most cases the required output of concrete will provide a reliable basis from which to calculate the capacity of the mixing plant and cement and aggregate requirements, and these in turn will indicate the capacity of the plant necessary to convey and distribute the mixed concrete.

For minor work requiring a comparatively small amount of concrete, an economical practice is to discharge the concrete direct into either hand trucks or wheelbarrows from which it is tipped and spread. For work in congested areas small petrol-driven trucks similar to that shown in *Fig.* 44 have many advantages.

For work requiring 100 cu. yd. or more a day concrete is frequently mixed at a central depot and transported to the work in specially-built vehicles (see *Fig.* 45). This method is speedy and efficient if there are suitable access roads to the site; it has been used for roads in built-up areas requiring 200 cu. yd. of concrete a day.

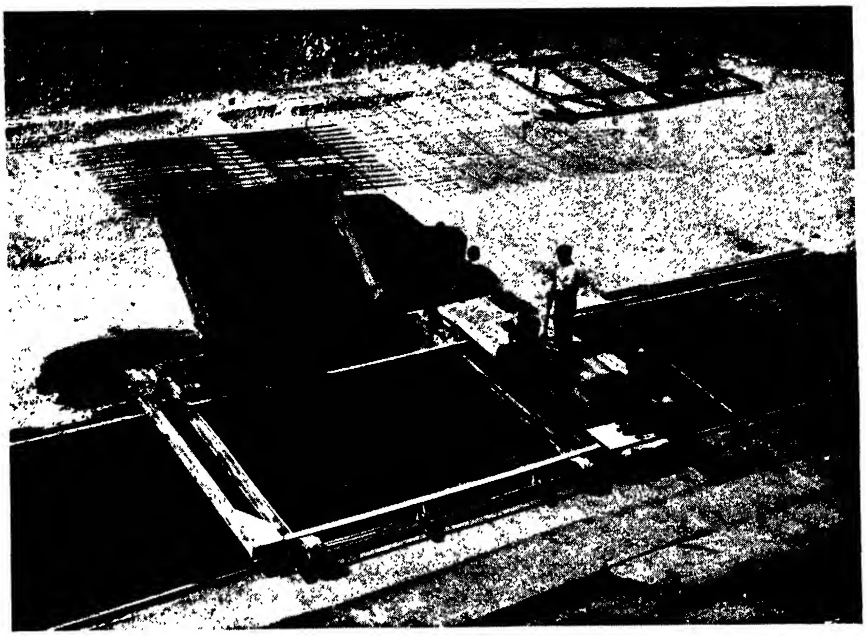


FIG. 45.—SIDE-TIPPING LORRY FOR DELIVERING CONCRETE

Vehicles used for transporting concrete should be of robust construction and designed so that their contents can be rapidly discharged. For hauls of up to about half a mile of concrete having a slump of 1 in. to 1½ in. there is little likelihood of segregation occurring during transit. Loss of moisture due to evaporation in warm weather must be avoided by ensuring that there is no delay in transporting the concrete and that the concrete is protected from the sun and wind. For longer hauls—up to one hour—trucks or wagons fitted with mechanically-operated agitators may be employed. These machines discharge the concrete freely at the specified consistency, but they can only be used satisfactorily where all points at which concrete is required are easily accessible and the possibility of delay is negligible. The transit mixer also offers advantages on small bridge and culvert construction requiring only a comparatively small volume of concrete.

Distributing and Placing.

The necessity for placing concrete soon after it is mixed is well known. Thirty minutes is usually accepted as the limit for Portland cement concrete in normal temperature conditions in the British Isles. This period may be extended in cool weather, but on well-organised work not more than 30 minutes should be required.

Concrete that is conveyed from a mixer in jubilee skips or hand carts should be deposited on a stage before being placed by the spreaders, who should place it so as to avoid separation of the coarse and fine particles. Alternatively the concrete may be discharged from a skip into the hopper of a mechanical distributor (*Fig.* 50) when the size of the work justifies mechanical distribution. On small works it is usual to employ a small mixer fitted with road wheels which is kept as close as possible to the face of the work and moved as concreting proceeds,

FIG. 46.—DEPOSITING CONCRETE FROM TIPPING SKIP ON TRACK ACROSS THE ROAD.

thus allowing the concrete to be shovelled into position from the point of discharge. For minor work an economical method of depositing concrete consists of a jubilee rail track fixed to the mixer carriage ; the mixer moves on rails laid parallel with the road, and the transverse track acts as a boom spanning the strip under construction. Concrete is discharged from the mixer into a small side-tipping skip (*Fig.* 46) which travels on the transverse track, thus permitting the concrete to be discharged at the face of the work.

Where space is limited and mixing has to be carried out some distance from the site, the methods shown in *Figs.* 44, 47 and 48 have many advantages. The concrete is loaded into side-tipping or end-tipping lorries or dumper trucks which discharge their contents quickly, thus causing the minimum delay to traffic.

Placing Concrete.

The need for placing and distributing stiff concrete mixes which cannot be satisfactorily consolidated by hand has resulted in the development of mechanical plant for this purpose. When applied to long stretches of road mechanical methods are more rapid than hand methods, labour is considerably reduced, and the use of a stiffer concrete is made possible ; they enable the use of a mix with a minimum amount of water which otherwise could not be economically spread

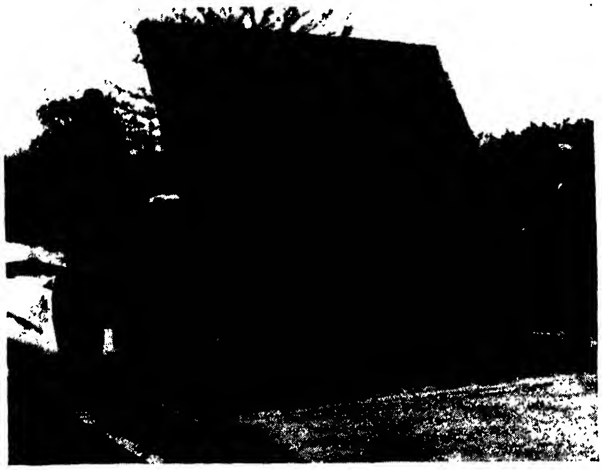


FIG. 47.—DISCHARGING CONCRETE FROM A DUMPER TRUCK.

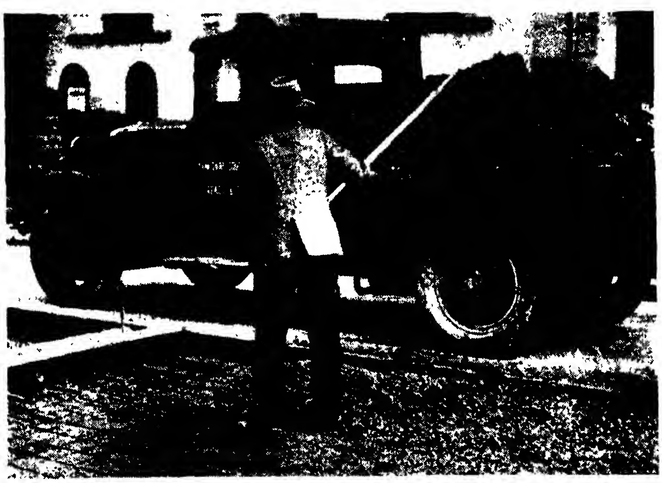


FIG. 48.—SIDE-TIPPING LORRY ABOUT TO DISCHARGE CONCRETE.

by hand. The mechanical placing of concrete for road slabs and similar paving may be carried out by either of the following methods.

BOOM AND SKIP.—This is generally a combined unit consisting of a mixer, boom, and skip or bucket (*Fig.* 49), the latter travelling along the boom and fitted with a bottom discharge gate for discharging into lorries or to the road.

MECHANICALLY-OPERATED HOPPER.—This is designed to hold 2 to 3 cu. yd. of concrete and is mounted on a power-operated carriage running either on the

FIG. 49.—COMBINED MIXING AND DISTRIBUTING PLANT.

FIG. 50.—CONCRETE MIXER WITH POWER-OPERATED HOPPER-DISTRIBUTOR BUCKET TRAVELLING ON GIRDER.

side forms or on flat-bottom rails. The hopper is fitted with bottom discharge mechanism ; it is adjustable in height and can be moved either transversely or longitudinally. The machine places and spreads the concrete to any required depth in one operation. *Fig.* 50 shows a typical installation used in Germany

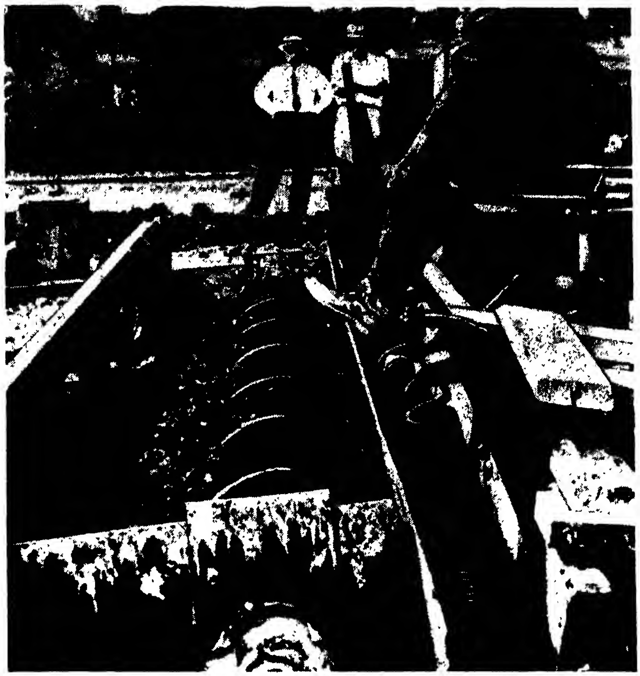


FIG. 51.—SCREW-TYPE CONCRETE SPREADER.

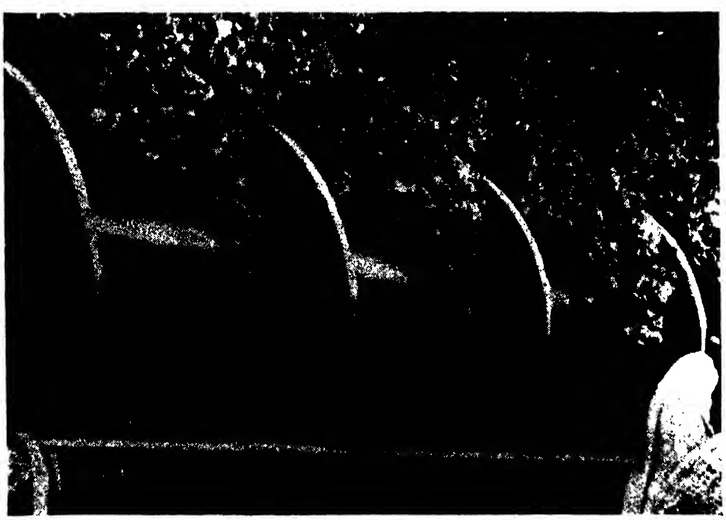


FIG. 52.—SHOWING OPERATION OF SPREADER SEEN IN FIG. 51.

for the construction of motorways. The mixed concrete is discharged directly from the mixer into the hopper-distributor, which spreads it evenly over the sub-base. Distribution by this method is speedy and efficient; the concrete can be placed evenly and simultaneously on both sides of any type of joint with the least disturbance of the joint and its supports.

Fig. 51 shows a screw distributor and *Fig.* 52 shows the worm-screw in action. Concrete is dumped on to the sub-base either from lorries or from a boom-and-bucket mixer; the screw revolves either forward or in reverse, moving through the concrete mass, distributing first to one side and then to the other until uniform distribution is effected. The screw is adjustable to any required

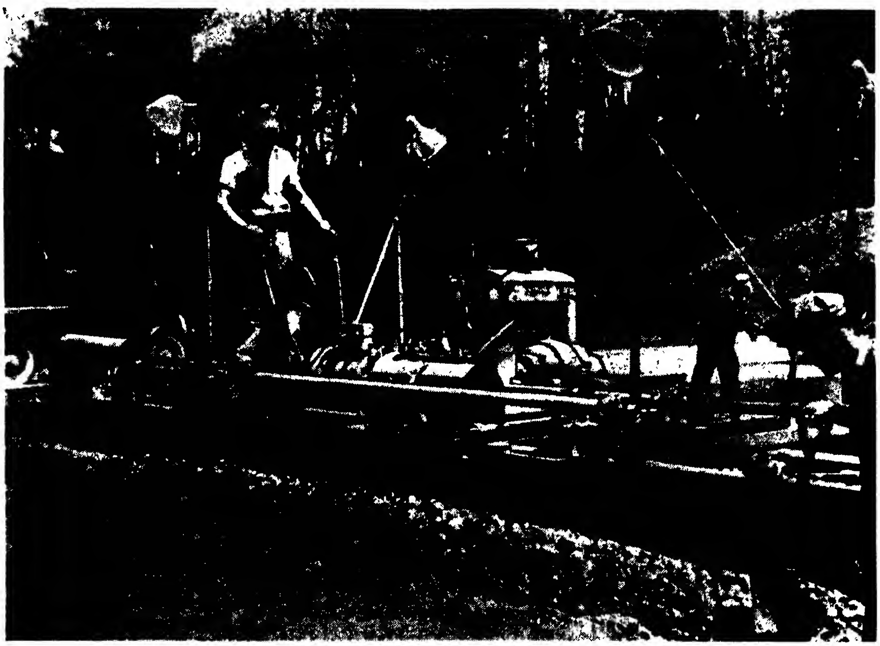


FIG. 53.—BLADE-TYPE SPREADER EQUIPPED WITH LIGHTS FOR NIGHT WORK.

height. One advantage of this method is that the concrete is given an additional mixing.

Fig. 53 shows a spreader or screed of the blade type. This may be an independent unit or, as is usual, attached to the finishing machine. The screed usually oscillates a few inches transversely and may or may not be vibrated at the same time. This machine is efficient provided the level of the concrete is controlled, otherwise two or more men depending upon the width of the slab, are required. to remove surplus concrete that has banked up in front of the screed or plate.

An American machine that has proved efficient for distributing large masses of concrete for roads and runways is the reversible-angle distributor, consisting of a comparatively small right-angle blade working on an adjustable horizontal shaft. The blade moves from side to side of the bay and during each complete traverse rotates through an angle of 180 deg.

A concrete spreading machine which was developed in the United States for the construction of concrete roads, and has since been used extensively in Britain on the construction of airfields, is shown in *Fig.* 54. The machine is adjustable up to 25 ft. in width, and the rate of operation has reached as much as 350 lineal feet of road 25 ft. wide per hour. It is only necessary to dump the concrete in front of the machine, and regardless of where the material is tipped

FIG. 54.—CONCRETE SPREADING MACHINE.

between the forms the machine spreads and levels it. The vibratory spreading and strike-off blades are independently adjustable in height.

Analysis of Methods of Mixing and Transporting Concrete.

The basis of the organisation of concrete road construction is the amount of concrete that can be produced by the mixing plant and transported to the site in a given time. If plant is used capable of supplying 400 cu. yd. of concrete per day, then adequate means must be provided for dealing with this volume in all other operations. There are many ways of supplying materials to the mixer and of delivering the concrete where it is required. It is doubtful if definite conclusions can be reached on the relative economy of these operations since many factors must be considered and each undertaking will vary.

ONE OR MORE MIXERS OF LESS THAN 1 CU. YD. CAPACITY.—The cement and aggregate are delivered to the site and removed to the mixer or mixers as required. The aggregate is usually stock-piled and taken to the mixer in barrows or jubilee wagons and the mixed concrete tipped into the bay being concreted. This is satisfactory for minor work where mixers of about 10/7 cu. ft. capacity are employed. For mixers of ½ cu. yd. capacity and over delivery of the concrete is best done by boom and bucket or by side-tipping wagons. The following are the principal points for consideration with such plant: (1) Comparatively inexpensive; (2) High labour costs feeding the mixer or mixers; (3) Comparatively small output (8 to 10 cu. yd. per hour per machine); (4) Insufficient control of concrete proportions if the materials are gauged by volume; and (5) Mechanical breakdowns are rare and can generally be dealt with speedily and cheaply.

One or more Mixers of 1 cu. yd. capacity or Over in Conjunction with a Central Batching or Proportioning Plant.—The aggregates are generally delivered to the site and stock-piled for drainage purposes, and then elevated to storage bins either by a grab or a bucket elevator. The cement is usually stored in sheds, but it is not unusual on large contracts for the cement to be delivered in bulk and fed to storage bins by pneumatic pump or enclosed elevators. After being weighed, the aggregates are discharged into lorries fitted with one-batch compartments or into dumper wagons. For extensive work side-tipping skips, each holding one batch, running on light railway track along the margin of the carriageway, are very efficient since a train of these skips may be drawn comparatively long distances by a low-powered petrol or diesel locomotive. The mixers are usually from 1 to 1¼ cu. yd. capacity of the single-drum type, fitted with a boom and bucket and running on power-operated tracks, or of the bridge type mounted on a travelling carriage spanning the full width of the carriageway (*Fig.* 50). The points for consideration are: (1) Comparatively expensive batching and mixing plant; (2) Low labour cost feeding the batching plant and proportioning materials; (3) Accurate control of concrete proportions; (4) Comparatively large output of concrete (30 to 60 cu. yd. per hour per machine); (5) The effect of a mechanical breakdown is serious.

Central Batching and Mixing Plant.—Similar arrangements for delivery, storage, and measurement of materials as outlined for the previous case apply. The mixers are generally of 1 cu. yd. capacity or more, requiring efficient plant for the transportation of concrete to the site. The range of operations is more or less limited since the delivery of the concrete is either by lorry or dumper truck or by jubilee skips. Special truck agitators may be employed if the range of operations is extended and the maximum time for delivery does not exceed one hour. Plant of this type is an essential feature of all road work requiring accurate and quick proportioning of materials. The plant may vary in size from the semi-portable type that can be transported as a whole from job to job to large installations of 300 tons capacity. Points to be considered are: (1) Comparatively expensive plant; (2) Low labour costs feeding bins and mixer; four or five men are required; (3) Comparatively large output; (4) Separate storage bins for the aggregates permit mixes of varying proportions and grading to be used; (5) Range of operations is limited unless special vehicles are employed; (6) The effect of a mechanical breakdown is serious.

Compacting and Finishing.

Thorough compacting ensures a dense and homogeneous concrete free from voids, honeycombing, and surface irregularities. The water-cement ratio theory only holds good for concrete that is fully compacted, so that it is better to have a little more water and ensure easy and thorough compaction than to use a comparatively dry mix which may be difficult to compact and finish in reasonable time.

Concrete having a water-cement ratio of about 0·50 to 0·60 can be well compacted by hand by means of a timber tamper weighing not less than 7 lb. per foot run. The adjustable cambered type is an advantage for work at intersections. Suitable tampers are illustrated in *Figs.* 55(*a*) and 55(*b*). If the paving is in two courses each must be tamped separately. The bottom course must be thoroughly compacted before the top course is laid, and not more than 30 minutes should elapse between the finishing of the bottom course and the laying of the top course.

Spreading and finishing the top course should be carried out in lengths of 4 ft. to 6 ft. This enables the spreaders to check the level of the finished surface and to fill in hollows or remove high spots. Tamping should proceed until a closely-knit dense surface is obtained. The aim of the first tamping operation (*Fig.* 56), should be compaction and screeding to the approximate level required. Subsequent tamping should advance about 3 in. at a time in the direction in which the work is proceeding; final tamping should be about ½ in. at a time until a level and dense surface is obtained.

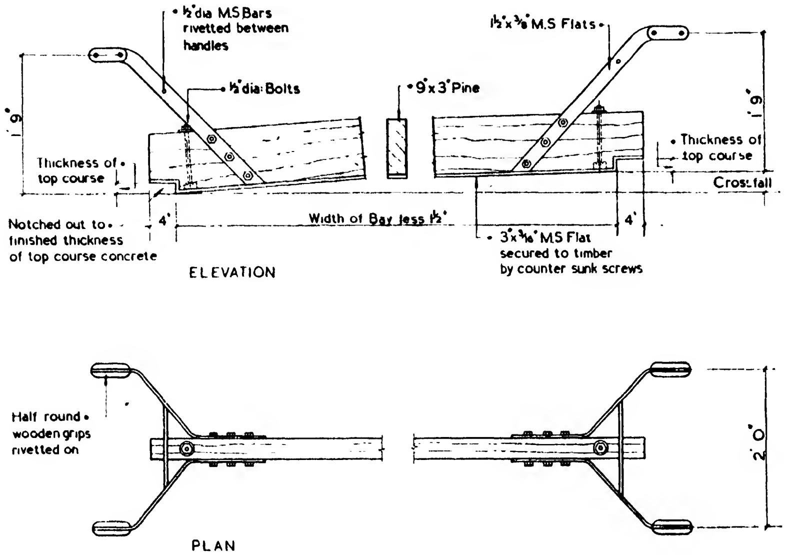
The speed and ease of finishing is increased if the concrete for the top course is mixed for at least three minutes; the increased workability obtained is of great advantage to the finishers on whom the speed of construction frequently depends.

HAND-FINISHING.—Three types of finish can be used, (1) The normal method of finishing with the smoothing board which gives the equivalent of a wood float finish and provides an ideal surface for all ordinary purposes; (2) The tamped finish which gives a ridged surface; and (3) The rough-surface finish consisting of large cubical stone standing proud of the surrounding mortar and usually specified for steep gradients.

Smooth Finish.—The advantages of the smoothing board finish are (1) Smooth riding due to the elimination of " waves " from the surface; (2) Removal of the ridges usually formed in a surface which has been finished by tamper only, and the absence of laitance; and (3) A true surface is quickly obtained, whereas by using tampers only it is often necessary to cover the ground many times to ensure a fair running surface.

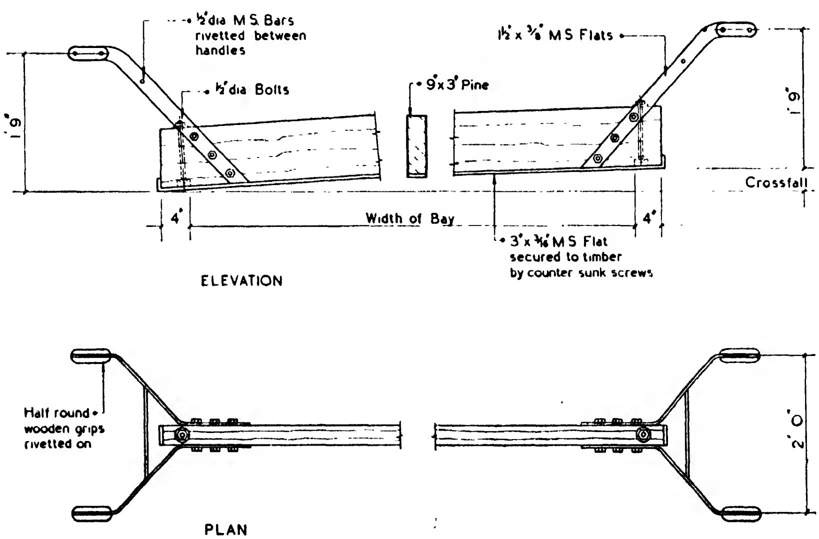
The shape of the finishing board [*Figs.* 54(*b*) and 57] must be checked from time to time against the tamper for camber and any necessary adjustments made. On some works the board has been discarded because of a difference in camber not being realised, with consequent tearing of the surface.

When a length of approximately 6 ft. of the surface has been tamped the finishing board should be used. A limited use of this tool must be made, two or three traversings being usually sufficient if the proportioning and grading of the aggregates are correct. The tool should be used with a to-and-fro movement



HAND TAMPER Nº 1.

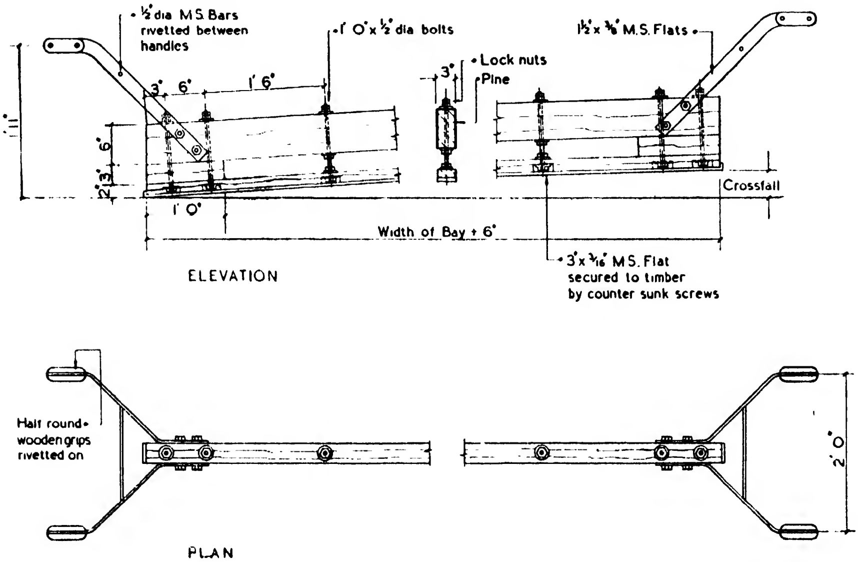
For final tamping half width of the bottom course of two-course roads



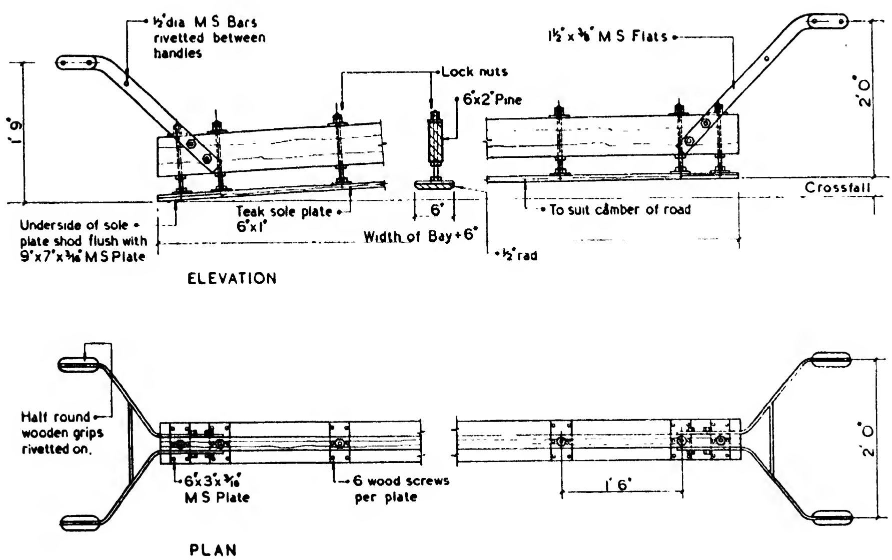
HAND TAMPER Nº 2.

Surface tamper for either one-course or two-course roads.

FIG. 55(*a*).—TYPES OF HAND TAMPERS.



ADJUSTABLE HAND TAMPER N° 2.



ADJUSTABLE SMOOTHING BOARD

FIG. 55(*b*).—HAND TAMPER AND SMOOTHING BOARD.

across the concrete with an advance longitudinally; it should be kept as flat as possible at first. At the final operation the front edge may be slightly tilted upward. Excessive use of this tool or its use as a tamper is detrimental as it brings an excess of fine material and laitance to the surface.

Tamped Finish.—In this country the method preferred is to stop the process with the tamping and make no use of the finishing board, but to proceed after tamping as mentioned later. It is obvious that care must be taken in this method, whether the surface is to be smooth or rough, to ensure that " waves " are eliminated if possible. The preference is really due to the idea amongst contractors that the use of the smoothing board decreases the output due to delay in finishing. This is proved to be a fallacy in practice. When the smoothing board is employed the amount of tamping necessary to produce a close-knit surface is materially

FIG. 56.—TAMPING THE SURFACE.

reduced, and the total time of the two processes is less than that otherwise expended on tamping alone.

As spreaders become accustomed to their work they become expert at packing the concrete correctly, but initially they are inclined to leave the concrete higher or lower than the proper level; this leads to undertamping where the surface is low and overtamping where it is high. If the concrete is spread at what appears to be the correct level to allow for tamping and then struck off, much of this uneven work disappears. A watch must be kept by the tampers to prevent the concrete riding over the side forms to avoid the finishing tamper working off concrete and not off the forms.

Rough-Surface Roads.—This type of surface is used on steep gradients, especially in districts where there is a considerable amount of horse-drawn traffic. The method of construction is similar to that already described. A large aggregate such as 2-in. stone is used in the top course, and the usual concrete mix can be modified subject to a void test being taken so to ensure that there is not an excess of surplus mortar when brushing is being completed.

For this type of construction a heavy iron-shod tamper about 4 in. wide is substituted for the lighter tamper used on the ordinary top course. This is used to get the general level; any small depressions may be eliminated by the use of hand tampers and the addition of concrete.

When the concrete is laid and beginning to set, all surface laitance is removed by stiff bass brooms and the aggregate exposed to the desired roughness. If a very rough surface is desired a little water may be applied to the surface by means of a rosehead watering can and the brushing continued.

FIG. 57.—TAMPER (IN FOREGROUND) AND SMOOTHING BOARD.

Checking Level of Finished Surface.

The surface should be checked for alignment by means of a 5-ft. straightedge as the work proceeds. A straightedge for this purpose is illustrated in *Fig.* 58. It is impossible to judge the finish of a road by eye owing to the deception caused by the laitance and wetness of the surface.

Finishing at Joints.

The importance of obtaining a true level of the concrete at joints has already been stressed—joint construction is a highly skilled operation only to be entrusted to skilled men. In no circumstances should the edges of the joints be finished before the concrete is in a proper condition to allow the jointing tool to be used effectively. The use of laitance or scum from the surface, or the addition of water, to aid workability should on no account be permitted. If the concrete is unworkable or too harsh, 2 in. or 3 in. of the concrete on each side of the joint for a depth of 1½ in. to 2 in. should be removed and replaced by well-proportioned and thoroughly compacted concrete, say a nominal mix of 1 : 1½ : 3 with ¾-in. maximum size aggregate.

The practice of fixing jointing material level with, or in many cases above, the finished level of the road cannot be recommended since this prevents continuous tamping over the joint. In such cases concreting should be stopped about 2 ft. from the joint line, the spreaders placing the concrete against the

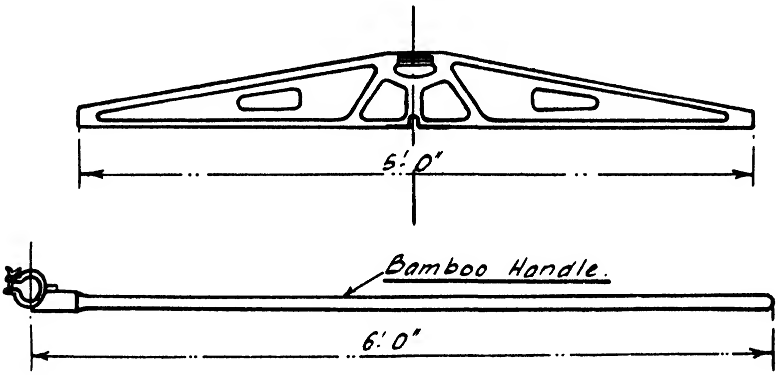


FIG. 58.—STRAIGHTEDGE FOR CHECKING SURFACE LEVEL.

joint filler and working back to the point at which concreting was discontinued. The men tamping and finishing should adopt the same procedure, otherwise laitance and excess moisture will be tamped forward and accumulate along the joint line; moreover, it is not easy to correct the amount of concrete under the tamper close to the joint, and slabs of slightly different level may result. The eye does not always notice this difference in level in time, as the joint filler breaks the line of vision; in any case a straightedge (*Fig.* 59) but preferably notched to

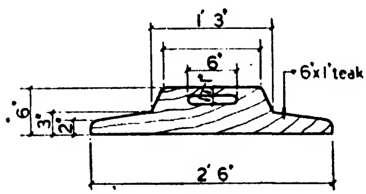


FIG. 59.—TEMPLATE FOR LONGITUDINAL JOINTS.

fit over the jointing material, should be used to check the level on each side of the joint.

TREATMENT OF EDGES.—The edges or arrises of all joints should be rounded. A radius of ⅜ in. has proved satisfactory for concrete made with gravel aggregate of 1½ in. maximum size; larger material, particularly broken stone of 2-in. gauge, is sometimes difficult to work at the edge of joints and may require a slightly wider radius.

The edges are rounded by a tool such as that shown in *Fig.* 60 and work should proceed as soon as the concrete is stiff enough. The proper time can only be found by trial, but the work must not be delayed too long. The edging tool should be manipulated so that a well-defined and continuous radius is produced, and a smooth, dense, mortar finish obtained. In shaping metal cavity joints the cutting edge of the tool should run on the flange of the joint and rest against

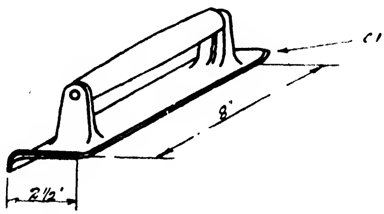


FIG. 60.—ROUNDING TOOL FOR FINISHING ARRISES OF JOINTS.

the vertical portion of the metal channel and so provide a well-defined space to receive the sealing compound. Joints for which a flexible filler is used provide no support for the rounding tool; therefore only slight pressure should be exerted on the concrete, otherwise inequality of level at the joint will result; in such

FIG. 61.—ROUNDING ARRIS AT EDGE OF SLAB.

cases, the tool should be run along the concrete as lightly as possible until a smooth face is obtained. *Fig.* 61 shows a longitudinal joint being rounded, and *Fig.* 62 shows a double edging tool for use at contraction joints.

There is always a danger of too much mortar being used in an effort to provide a good-looking joint. This should be avoided and the arris formed of fine well-graded concrete at least equal in proportions and strength to that used for the slab. Some engineers, in order to ensure that the joint edges do not chip or break down under traffic, employ a special mix of granite chippings, sand, and cement which, when thoroughly compacted, gives excellent results.

The following treatment is necessary in the case of joints in road slabs for which a large aggregate say, 1½-in. to 2½-in. gauge is used,. Timber battens 2½ in. wide and 2 in. deep are placed on each side of the joint and concrete tamped and finished against them; the battens are then removed and the space they occupied filled with concrete made with granite chippings of ¾ in. maximum size, in the proportions of about 1 : 1½ : 3; the arrises are then rounded as already described.

FIG. 62.—DOUBLE EDGING TOOL FOR FINISHING ARRISES OF JOINTS.

Compacting by Machine.

Mechanical compaction is usually carried out by external or internal vibration or by tamping machines. Mechanical compaction has the following advantages. (*a*) Much drier mixes than can be compacted by hand can be placed satisfactorily. Such mixes, owing to the reduction in their water content, produce high early strength concrete which, in turn, is more able to resist stresses due to shrinkage and changes of temperature; (*b*) For a given cement content an increase in flexural and compressive strength of about 10 per cent. can be obtained; (*c*) Concrete of the proportions of 1 to 7½ will give at least as high a strength as 1 : 6 concrete of the same water-cement ratio compacted by hand methods.

The compaction of unreinforced slabs not greater than 8 in. in depth is usually carried out in one operation, whilst two operations—one being at mid-depth—may be necessary for slabs of greater thickness, depending upon the type and efficiency of the machine and the workability of the concrete.

In the case of reinforced slabs the concrete must be thoroughly compacted along each plane of reinforcement and the position of the reinforcement ensured during subsequent tamping and finishing operations. It is therefore desirable to compact the concrete below the steel as a first operation and not to rely entirely on the passage of the finishing machine over the surface, since lack of bond between the concrete and steel may arise with some mixes of comparatively stiff consistency. For minor work an efficient and inexpensive compacting unit may be provided by mounting two or more vibrating elements on a stout timber board or on a steel tee similar to that shown in *Fig.* 63. This type of apparatus is easily moved by hand and may be operated either electrically or pneumatically: the former method requires a portable petrol generator set and the latter an air compressor. The strength of concrete compacted by these machines shows a marked increase in strength over that of similar concrete compacted by hand-operated tampers. The best results will not be obtained unless

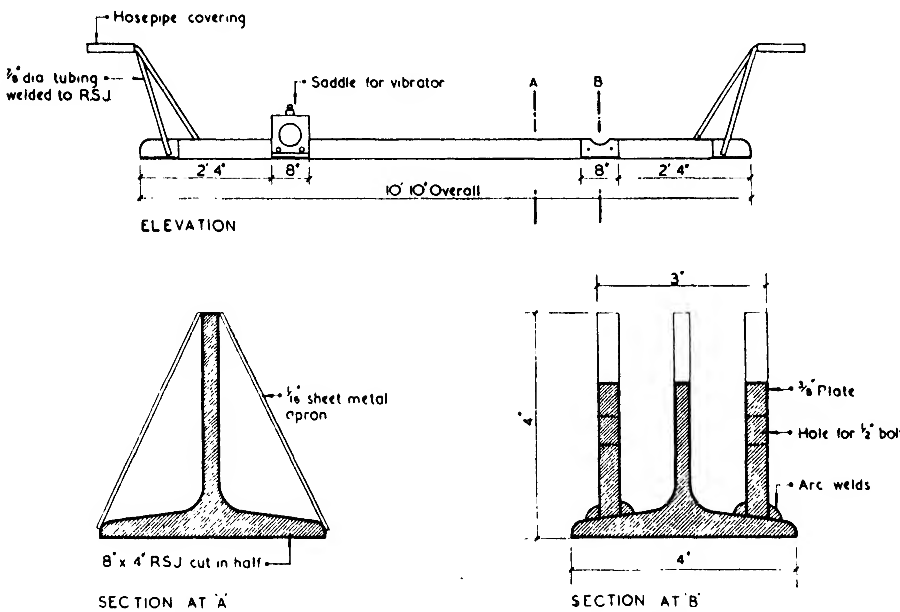


FIG. 63.—VIBRATING TAMPER FOR ESTATE AND SIMILAR ROADS.

attention is given to those details which are of importance in any concreting work. The main precautions to be observed are the following.

THE FOUNDATION.—Some of the energy applied to the compaction of the concrete will be transmitted to the foundation, and further consolidation of the foundation may take place if it has not been thoroughly consolidated. In some American tests it was found that after the passage of a vibrating finisher the forms had settled ⅛ in., thus producing a slight increase in the thickness of the concrete and probably errors in alignment.

SIDE FORMS.—As it is common practice for distributing and finishing machines to run on the side forms it is essential that these be rigid, as on this depends the evenness of the finished surface and the thickness of the slab. On weak foundations the forms should be supported on a base of lean concrete to ensure that deformation does not occur during construction.

Supply of Concrete.—It is important that a smooth and regular supply of concrete be fed to the distributing machines, and that the concrete is of uniform quality. A mixer or mixers of large capacity are necessary, capable of giving a batch of from 1 cu. yd. to 2 cu. yd. The effects of non-uniformity in the proportions of the concrete are more pronounced for concrete compacted by machine than by hand and may result in the surface having a patchy appearance.

Proportions of Concrete.—The best proportions will depend to a large extent upon the type of machine used. For one type of machine satisfactory compaction and finish may be obtained with a relatively under-sanded mix, whereas for another type a higher sand content may be necessary. The most suitable proportions of concrete for any machine should be determined by trial. For suggested proportions, grading of aggregates, etc., see Chapter VII.

Consistency of Concrete.—It has been found in this country and on the Continent that a concrete which has no slump and just balls in the hand when squeezed can be adequately consolidated by the best machines. American specifications require vibrated concrete to have a slump not less than 1 in. nor more than 1½ in. American practice, however, consistently uses a wetter mix for road work. It must be emphasized that the essential advantage to be obtained from machine compaction is that it permits much drier (and consequently much stronger) concrete than that used for hand-tamped work. A mix having a higher water-cement ratio will speed up the processes of distribution, compaction, and finishing with a possible saving in time but only by a corresponding loss in strength.

It is sometimes contended that concrete with a strength of 5,000 lb. per square inch at 28 days and a slump of 1½ in. to 2 in. will not only satisfy most road specifications but will be cheaper because time and labour are saved in distribution, compaction, and finishing. This is admitted, but in order to make a true comparison the case for concrete having a stiffer consistency must also be considered. For all practical purposes a slump of 1½ in. represents a water-cement ratio of about 0·50, which should produce concrete having an average crushing strength of approximately 5,000 lb. per square inch at 28 days. If the water-cement ratio is lowered to, say, 0·45 to produce a concrete having no slump but suitable for vibration, its compressive strength would be raised to about 6,000 lb. per square inch at 28 days. Since this concrete may be slightly more expensive than that with the higher water content, owing to the extra time required for distribution and compaction, a saving might be effected by one of the following alternatives : (*a*) A slight reduction of the thickness of the slab made possible by the higher strength, thus saving excavation, concrete materials, and labour ; (*b*) Maintaining the slab thickness and reducing the cement content by approximately 10 to 15 per cent. to give a concrete of equal strength to that having 1½-in. slump.

Tests.—Periodical tests to check the grading, silt content, or cleanliness of the aggregates must be carried out and means taken to ascertain their moisture content. Cubes should be compacted to maximum consolidation, and not tamped in the standard manner laid down in the Code of Practice which is normally intended for concrete that is to be compacted in place by hand. The test cubes should represent as closely as possible the condition of compaction as carried out in the work.

SPEED OF CONSTRUCTION.—The speed of the work will depend largely on the organisation provided to ensure the continuous use of the plant. This will include mixing plant of adequate capacity and efficient means of transporting the concrete to the point required, together with suitable plant for its distribution.

The normal working speed of finishing machines is about 2 ft. per minute, most machines being capable of a forward speed of from 1 ft. to 8 ft. per minute and 2 ft. to 16 ft. per minute in reverse. The normal rate of progress on the German motorways, 8½ in. thick and 24 ft. wide, was 220 yd. per 8-hour day, equivalent to about 1 ft. 4 in. per minute. The average rate of progress of a machine used on a dual carriageway in this country, 8 in. thick and 11 ft. wide, was 61 ft. per hour, whilst an output of 190 ft. per hour has been attained in America for paving 8 in. thick and 20 ft. wide. Assuming a thickness of 8 in. and three traverses of the machine, construction can generally progress at 2 ft. per minute on any width of road within the capacity of the machine.

With the machines at present in use the best rate of advance is between 1 ft. 3 in. and 2 ft. 6 in. per minute for concrete having a water-cement ratio of about 0·43, increasing to about 6 ft. per minute for concrete with a water-cement ratio of 0·5. The actual time required for complete compaction of the concrete depends upon its workability and the depth of slab. Full compaction of concrete of low workability can only be achieved if every portion of the slab is vibrated for at least 30 seconds.

COMPACTING AND FINISHING THE SURFACE.—Whenever possible, single course paving up to 9 in. thick should be levelled, compacted, and finished in a single traverse of the machine. For this purpose a finisher is required that possesses two vibrating units, namely, a compacting unit working at a frequency of from 3,500 to 4,000 per minute and a finishing unit having a frequency of not less than 2,000. The screeding plate should be capable of operating in a position that will strike off the concrete at a sufficient height above the top of the forms to allow for full compaction by the vibratory unit, which should rest directly on the concrete and be adjusted to give uniform vibration over the full width of slab. Prolonged vibration over a given area should be avoided and only sufficient traverses of the machine made to ensure the required density and finish; the last traverse should be a continuous run of at least 30 ft.

SURFACE TEST.—General practice is to examine the surface immediately after the final passage of the finishing machine and test for level by means of a 10-ft. straightedge, clearly marking all high and low spots, all variations of more than ⅛ in. being immediately corrected. American practice requires this test to be carried out not sooner than twelve hours after the concrete has been finished; where the departure from the correct cross section exceeds ¼ in. the paving should be removed and replaced, any area so removed being not less than 10 ft. in length nor less than the full width of the slab. It is somewhat difficult to understand why this test is carried out at such a long interval after the concrete has been finished unless it is for the reason that it will take some time for surface water left by the vibrator to disappear, a contingency that is only likely to arise with concrete having water-cement ratio of about 0·50 or more. Provided irregularities are corrected by skilled men who know what materials to use and when to use them, minor adjustments are best made before the concrete has hardened.

CHAPTER IX

JUNCTIONS, CURVES, AND SUPERELEVATION

In the construction of road junctions each case must be treated on its merits, and it may be necessary to make and plot a survey of the site before work is undertaken. The main point is to eliminate a costly system of formwork or special tampers. Since levels theoretically worked out do not always give the best results it may sometimes be advisable to " sweeten " the falls by eye after the forms have been set if the final result is to be satisfactory. The principal points that require consideration are (1) Easy formation of the junction without the use of special tools or forms, (2) Provision of suitable falls to gullies and avoidance of sudden changes of level, and (3) Avoidance of acute angles in the road slab.

Transition Bays.

Transition bays are introduced to effect a gradual alteration in the shape of a road surface. Such changes should be effected by easy stages if the result is to be pleasing to the eye and the junction or crossing easily negotiated by fast traffic.

Where tamping is carried out at right-angles to the kerb the shape of the tamper decides the shape of the road surface, and it is therefore impracticable to change the camber gradually. For this reason longitudinal tamping is recommended for transition bays, a straight tamper being operated parallel to the kerb. As a rule any alteration in camber can be produced in a distance of 40 ft. or 50 ft., three transition bays each approximately 15 ft. long being general practice. Where possible the natural run of the crown of the road should be left undisturbed and the channels set with uniform falls. The position of the crown and channel at any intermediate point can be boned in.

Assume that the carriageway has been completed to the point where the change of camber is to commence. The first step is to fix distant pegs marking the continuation of the line and level of the crown and channels. Intermediate pegs are then boned in at intervals of, say, 15 ft. on the lines of the crown and the channels, and at the end of each 15-ft. bay forms are set to the contour indicated by the pegs. A policy of perfection would require forms with shaped ends, but in practice the use of two straight forms from the crown to either channel is satisfactory. When the forms are set, longitudinal tamping with a straight tamper produces the gradual alteration in the camber.

Junctions.

Fig. 64 shows the junction of a main and side road where the main road is 30 ft. wide and is to be laid in half widths. The side road is 16 ft. wide and is to be laid full width. The following method can be adopted. The main road having been concreted up to the line HA, the half-width panel ADDA is laid continuing the same camber as the main road. The side road is also laid to its normal camber as far as KK, followed by three full-width transition bays between K and B, as described in the preceding paragraph. The point C on BB continues the line and level of the crown of the side road, while point C on DD is likewise on the crown of the main road. A form is laid along CC so that a sudden change of level is avoided. This is accomplished by making saw cuts

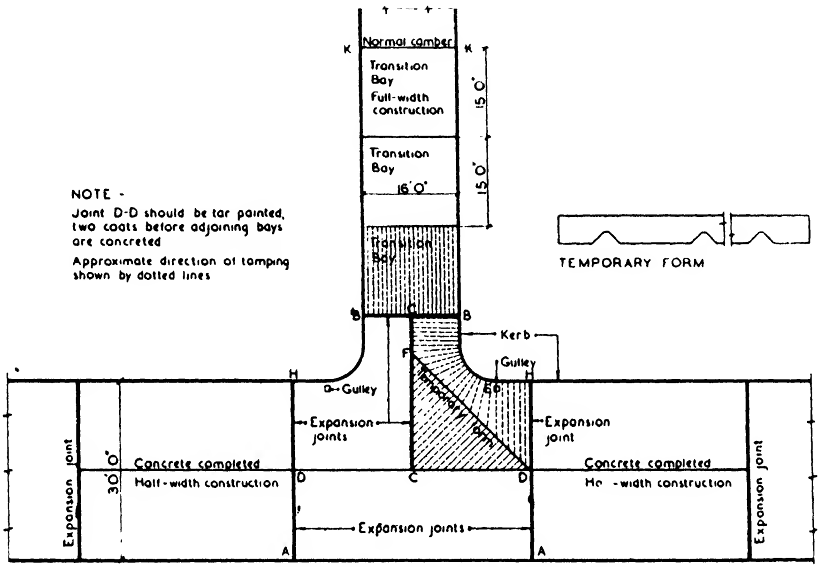


FIG. 64.—JUNCTION OF MAIN AND SIDE ROAD.

in the form and producing vertical curves which will work in to suit any longitudinal fall of the side road and the camber of the main road. The fall should be tested with a level from a few points on CC, taking care that E (where the gulley will be placed) is the lowest point. The form CC is now firmly fixed and a temporary form DF is laid. The panel BCFDH is now concreted, and tamped

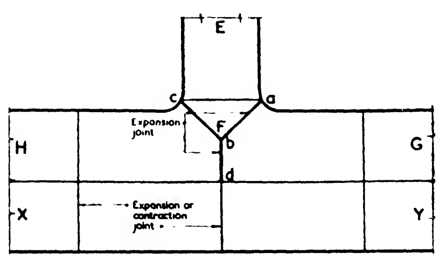


FIG. 65.—JUNCTION OF MAIN AND SIDE ROAD.

radially from the kerb to the road centres and to DF. The temporary form DF is not removed until panel CDF is concreted. When this half of the junction is laid the opposite half is similarly constructed, maintaining the falls of the main road.

Another method is to set along the lines ab and bc (*Fig.* 65), two light forms cut to the oblique camber of the road. These are set so that their top surfaces are level with the top of the side forms at a and c and with the finished level of the centre of the road at b. Assuming that road EF is concreted first, the triangular portion abc is tamped transversely between ab and bc ; beyond this the surface is tamped from the side forms. Before the road GH is concreted, forms ab and bc are removed and the road surface at the junction is tamped between the finished concrete surface along cbd and abd and the side forms GH. Beyond the junction the slab GH is tamped from the side forms to the crown line of the already-concreted half-width XY. A joint should be inserted along abc and bd and continued across the half width XY.

In a town where many square junctions occurred in one street, a special long tamper was made for the junctions and reached from the crown A to the kerb C (*Fig.* 66). In another, where the work was complicated by the main road having a " hanging " level, and the concrete was laid in two courses, the bottom-course was placed first over half the junction. Battens about 2 in. by

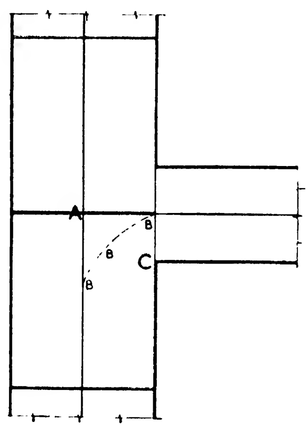


FIG. 66.—SHOWING USE OF SPECIAL TAMPER FOR SQUARE JUNCTION.

2 in. were then placed along the line BBB (*Fig.* 66) at such levels as to ensure that no hollows were left in the road. The top course was tamped from this line to the kerb at C by an ordinary tamper and from there to the crown by a straightedge. The battens were then removed and the spaces left were filled in and finished off with a float. In a third composite method the bottom course is laid continuously and the top course tamped on the alternate-bay principle between battens ; the latter are immediately removed and the space filled in.

The following method proved effective in Scotland, where street EF and part of street GH (*Fig.* 67) were being reconstructed with a concrete surface and provision had to be made for concreting part (JH) of street GH at a future date. Concreting started in street EF and the usual forms were laid alongside the kerbs up to points a, b, c, and d. From a to b and from c to d special 1-in. timber forms were laid. These special forms were cut to the standard camber for concrete roads in the district. The usual form was laid along the centre line and the concrete was tamped with a tamper cut to a circular camber, except from a to b and c to d where a straight tamper was used and worked from the centre and cambered forms. Although the camber was changed from circular to straight between the end of the kerb radius and points a, b, c, and d, the alteration cannot be detected by eye. An expansion joint was inserted along the line ab between the concrete slabs, and two rows of setts on a concrete foundation were laid along cd between the concrete and the existing macadam surfaces. As the roads carry fairly heavy steel-tyred traffic, small triangles at each corner were filled with granite setts laid on concrete to counteract the grinding effect of traffic close to the corners; the setts can be replaced easily when worn. If the whole street GH could have been laid first a special camber-board would not have been required at ab, as tamping could have been carried out between the concrete road surface at ab and the centre form on road EF.

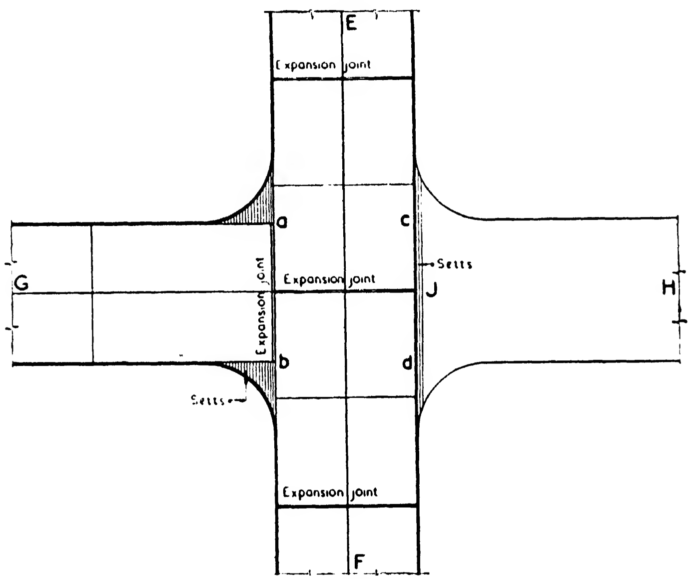


FIG. 67.—JOINT BETWEEN CONCRETE AND OTHER SURFACING.

Simple Square Crossing.

Fig. 68 illustrates a method of constructing the crossing of two 16-ft. carriageways, the points to be noted being as follows. (*a*) In setting out, the levels of the two crowns are carried straight through, the points P_1 and P_2 being on the crown of one road and Q_1 and Q_2 on the crown of the other. This, combined with the 18-ft. dimension, fixes the line and level of the forms around the space P_1, Q_1, P_2, Q_2. (*b*) Channels are set out to give constant falls to the gullies wherever the latter may be situated. (*c*) The bays A_1, A_2, A_3, and A_4 are transition bays in which the shape of the road is changed from a parabolic camber at X, to two straight cross falls from crown to kerb at Y. (*d*) The joints in the cruciform area Y_1, Y_2, Y_3, Y_4, should be preferably tongued and grooved and the slabs sufficiently thick to permit this construction. Alternatively the use of dowel bars is good practice. (*e*) The concreting of the square panel P_1, Q_1, P_2, Q_2,

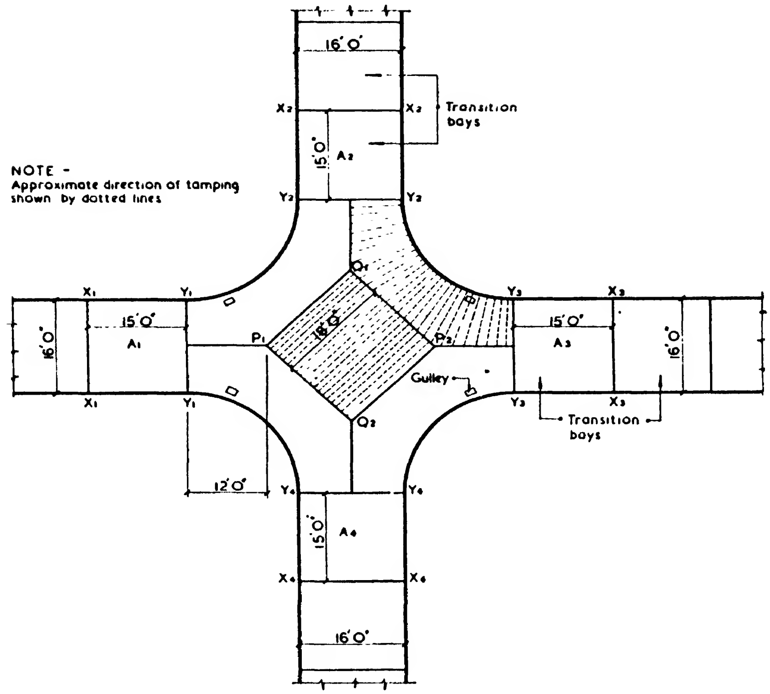


FIG. 68.—SIMPLE SQUARE CROSSING.

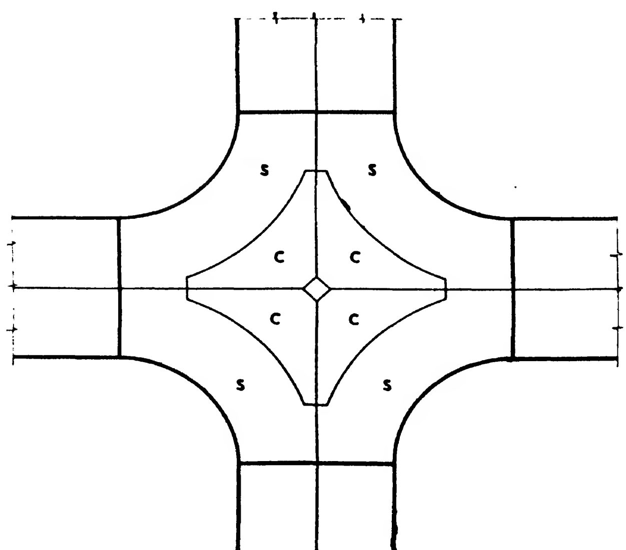


FIG. 69.—SIMPLE SQUARE CROSSING.

should be left until the last. The four L-shape panels at the corners should be tamped radially with a slightly cambered tamper, otherwise the bays will appear to be convex. The centre square should be similarly treated, the tamper being worked off the finished concrete of the four surrounding panels.

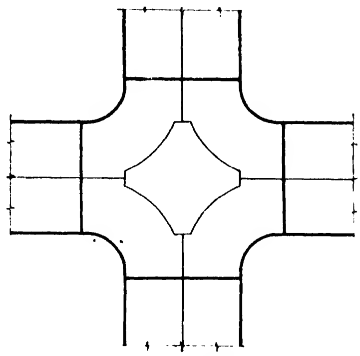


Fig. 70.—Simple Square Crossing.

In junctions of the star type the work is divided into bays meeting at the intersections of the centre lines of the two roads, and further divided for tamping transversely to the centre lines. The diagonal side forms must be cut to the correct camber. Junctions of roads up to 20 ft. wide have been successfully carried out on these lines, but for roads of greater width the maximum transverse tamp (that is, at the radius kerb) becomes excessive.

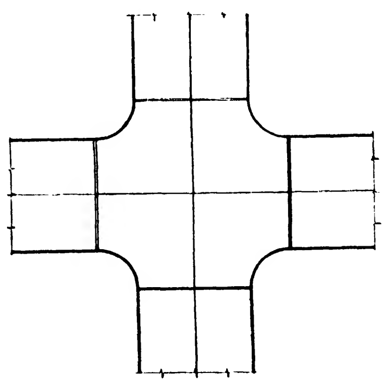


Fig. 71.—Simple Square Crossing.

In the method shown in *Fig.* 69 strips are constructed round each sweep S leaving four central bays C. At very large junctions a second series of strips can be placed between the bays S and C. The width of the bays S is one-half the normal width of the road. Acute-angle corners in bays C are avoided by incorporating in the bays S any part of bays C which is less than 2 ft. wide. Other arrangements of joints for constructing square junctions are shown in *Figs.* 70 and 71.

Fig. 72 shows the junction of a 24-ft. and a 16-ft. roadway which required a larger bellmouth than if the lesser width had been the intersecting road. The dotted lines show the position of the contraction joints, and the figures enclosed

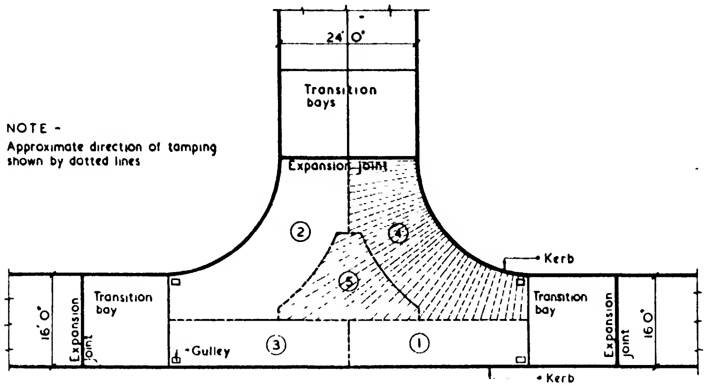


FIG. 72.—JUNCTION OF 24-FT. AND 16-FT. CARRIAGEWAYS.

in circles denote the order in which the bays were concreted. The side forms were placed so that specially-cambered screeds were not required, and a maximum length of 30 ft. was selected for the bays. Acute angles were avoided.

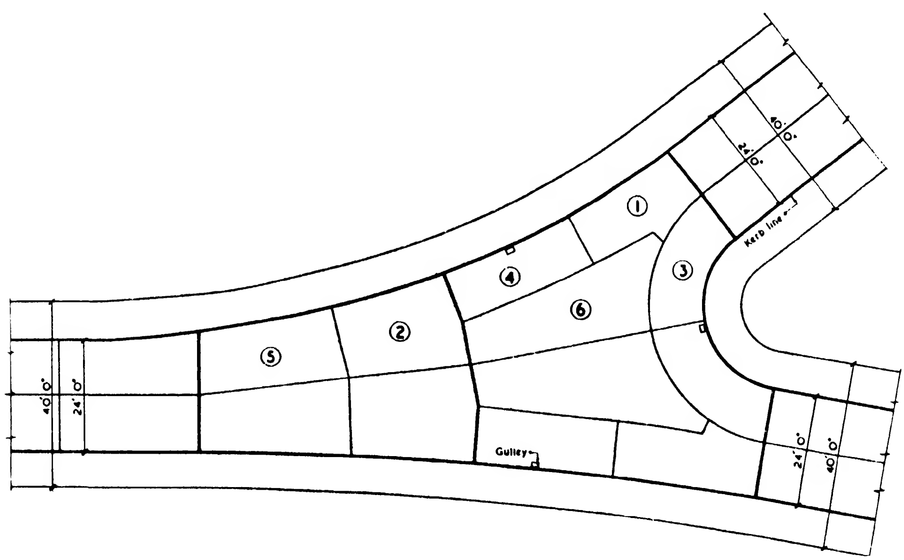


FIG. 73.—JUNCTION OF 24-FT. CARRIAGEWAYS.

Fig. 73 shows the junction of two 24-ft. carriageways and the position of the temporary forms for joints, the figures in circles being the order in which the bays were concreted. The positions of the gullies and the falls should be determined to prevent flooding at the junction.

Fig. 74 illustrates a junction of an estate road with a main road and a service road where a number of complications were encountered. An estate road (20-ft. carriageway) running from south to north on an ascending gradient of 1 in 50 was required to join a main road from west to east on a descending gradient of 1 in 30. About 50 ft. from the kerb of the main road a service road (16-ft. carriageway) leads to the east from the estate road, and has a descending

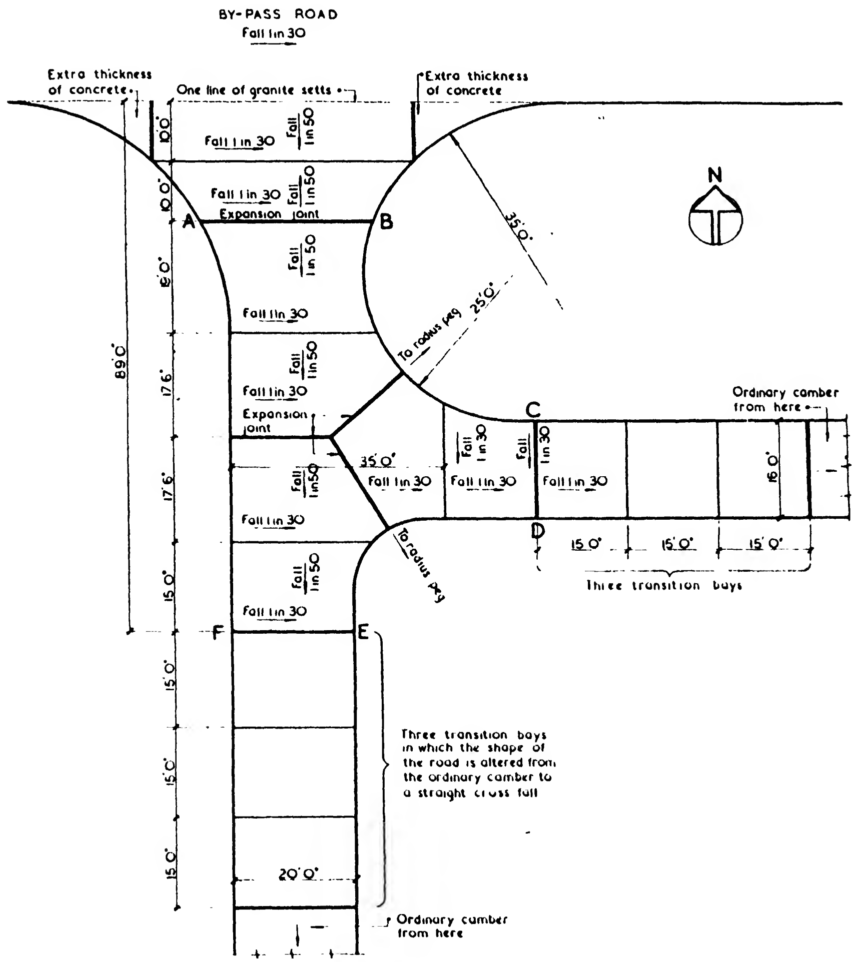


FIG. 74.—JUNCTION OF MAIN ROAD AND ESTATE ROADS.

gradient of 1 in 30. It was inadvisable to lead the estate road in with an immediate fall from the main road, since a choked gully in the main road would flood the estate road. For this reason an artificial rise had to be introduced on the estate road; in addition, the local authority required the first 10 ft. of the estate road to be laid on a downward gradient of 1 in 50 in continuation of the camber of the main road in view of the possible future widening of the latter. From north to south along the estate road the surface for a distance of 89 ft. has a cross-fall of 1 in 30 from west to east. The longitudinal gradients from north to south are a fall of 1 in 50 for the first 10 ft., a rise of 1 in 50 for 10 ft., and thereafter a steady fall of 1 in 50. The whole area ABCDEF is a plane surface having falls of 1 in 50 from north to south and 1 in 30 from west to east, and the straight cross-falls on the service road and estate road at CD and EF are gradually converted into normal cambers by three transition bays in each case. In the diagram expansion joints are indicated by heavy lines and tongued-and-grooved contraction joints by thin lines.

Fig. 75 shows the method adopted when forming a junction where three roads of different widths met. Bays a, b, and c were laid first, being tamped off the side and centre forms. They were laid at such intervals that traffic could use one side while the next was being concreted, and when they were all completed the triangular portion d was filled in and tamped with a very slightly

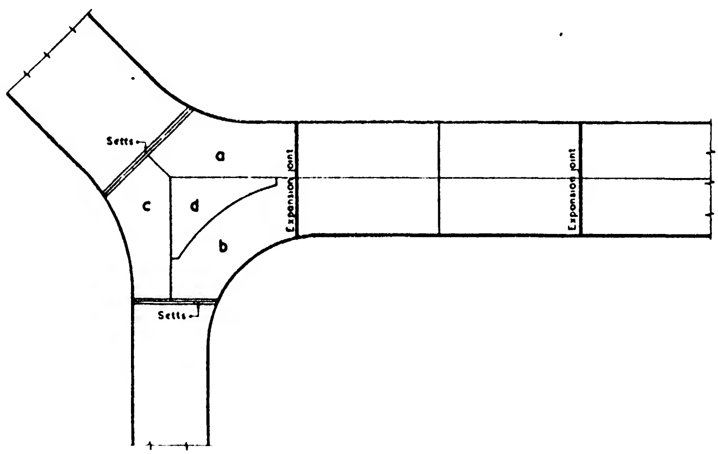


FIG. 75.—JUNCTION OF THREE ROADS.

cambered tamper. The tapered points on the triangle were stopped off, so that at no part is the slab narrower than 2 ft. As the area of concrete at the junction is large, expansion jointing was inserted all round the triangular portion. The whole slab was, as usual, separated from the kerb by bituminous material.

If the standard cambered tamper is used it is necessary, in order to give a "sweet" camber across the roadway at the triangular portion, to raise the centre forms adjacent to and around the triangular portion slightly above the normal calculated camber level. Alternatively the centre forms can be kept at their calculated levels, when the slabs adjacent to the triangle should be tamped with either a straight or very flatly cambered tamper. A modification of this method (*Fig.* 76) has been used at the junction of concrete and macadam roads where the concrete roads are widely bell-mouthed. See also *Fig.* 72 for details of construction. This method is not recommended in cases where the junction is subject to heavy traffic unless the depth of the slab is at least 7½ in. In order to avoid having a small tapered bay at the centre of the junction, half-width construction should be continued between the tangent points of the curve and the line of the stone setts.

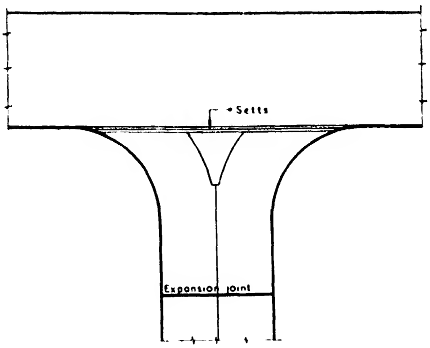


FIG. 76.—JUNCTION OF CONCRETE AND MACADAM ROADS.

The junction of the Guildford-Godalming by-pass road with the Stoke road, constructed to the design of Mr. W. P. Robinson, M.Inst.C.E., then County Surveyor of Surrey, is shown in *Fig. 77*.

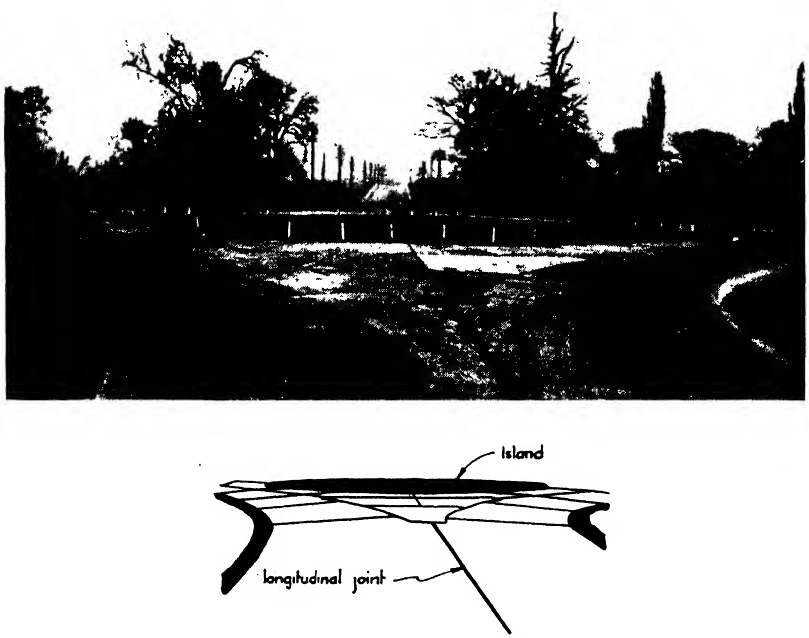


FIG. 77.—JUNCTION ON GUILDFORD-GODALMING BY-PASS ROAD.

Many road intersections are now being arranged to provide a gyratory system of traffic, and embody island sites or other forms of construction suited to the traffic of the locality. *Fig. 78* shows the junction and paving arrangement at the roundabout at the intersection of the Horsham road and the Crawley by-pass road constructed to the design of Mr. A. Floyd, M.Inst.C.E., County Surveyor of West Sussex.

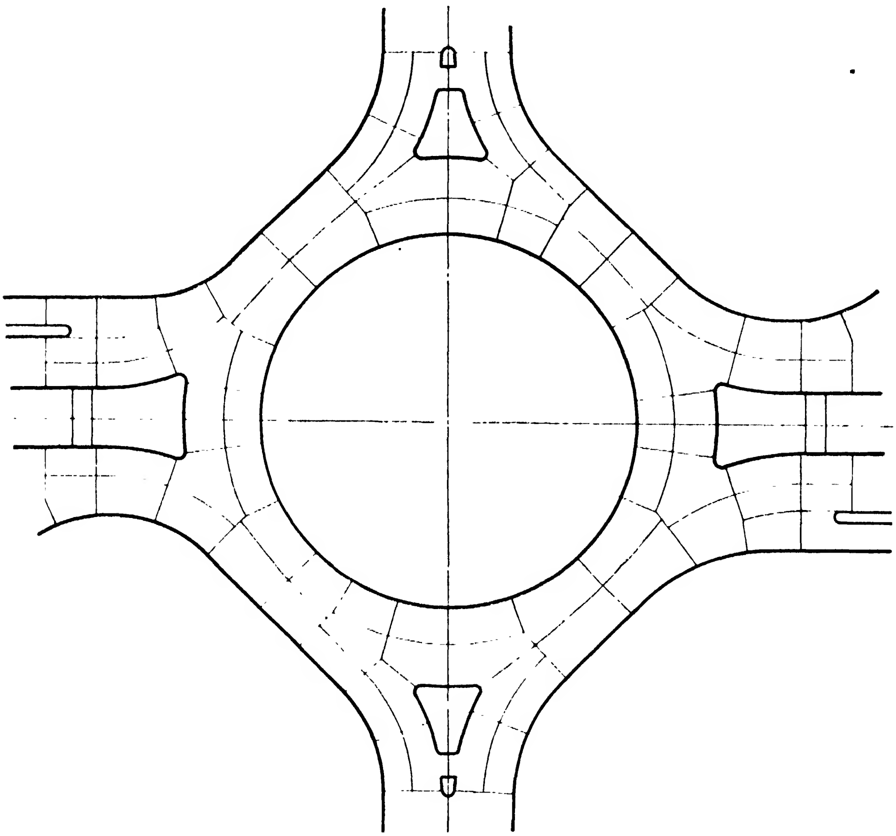


FIG. 78.—ARRANGEMENT OF CONCRETING OF ROUNDABOUT AT JUNCTION OF THE HORSHAM ROAD AND THE CRAWLEY BY-PASS ROAD.

Roundabout with Island.

Fig. 79 shows a sequence for concreting a roundabout 50 ft. in diameter, consisting of a 16-ft. carriageway encircling a central island 18 ft. in diameter, the roundabout being situated at the end of the 16-ft. carriageway. The main features are (*a*) The levels indicated are intended to enable gullies to be dispensed with in the roundabout, (*b*) the bay A is a transition bay in which the shape of the road is changed from a parabolic camber at XX to two straight cross-falls from crown to channels at YY, (*c*) all joints shown are tongued and grooved contraction joints, and (*d*) all panels within the roundabout are tamped radially with a straight tamper.

Fig. 80 illustrates an oval with an island in the centre on a long estate road. In this case the 18-ft. carriageway is divided into two 16-ft carriageways which pass on each side of an island 60 ft. long and 38 ft. wide. The design follows the same lines as those of the previous example, the camber being altered from a curve to two straight cross-falls in the transition bays at either end. It will

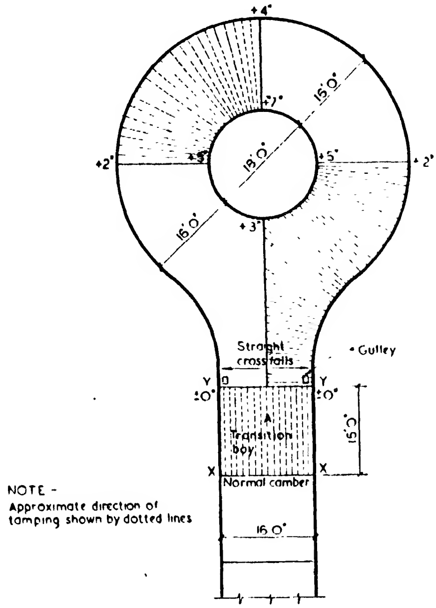


FIG. 79.—ROUNDABOUT WITH ISLAND AT END OF CUL-DE-SAC.

be noted that in *Figs.* 79 and 80 the fall is against the traffic, a matter of small importance for estate roads where traffic is inconsiderable. In the case of

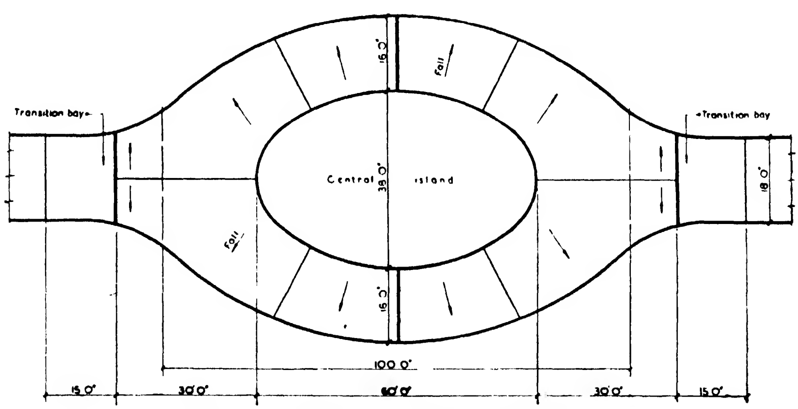


FIG. 80.—ISLAND ON A LONG ESTATE ROAD.

main roads the fall should be towards the central island whose larger diameter offers better facilities for the collection of surface water than that of the small island shown in *Fig.* 79.

Fig. 81 illustrates a roundabout with a central island at the crossing of two roads on the Springfield estate at Colindale. A 20-ft. carriageway with a longitudinal fall of 1 in 20 crosses a 16-ft. carriageway with a fall of 1 in 50. The roundabout is 66 ft. in diameter and the island 20 ft. in diameter. Advantage was taken of the natural falls to simplify the surface drainage of the roundabout and the whole of the space was laid as a plane surface having a fall of 1 in 20 in one direction and 1 in 50 in the other. In setting out the work, four pegs A, B, C, and D were set at the corners of a square with a side 66 ft. long situated as indicated in the sketch. The levels of the pegs were calculated to give a fall of 1 in 20 from A to B and from D to C and a fall of 1 in 50 from A to D and

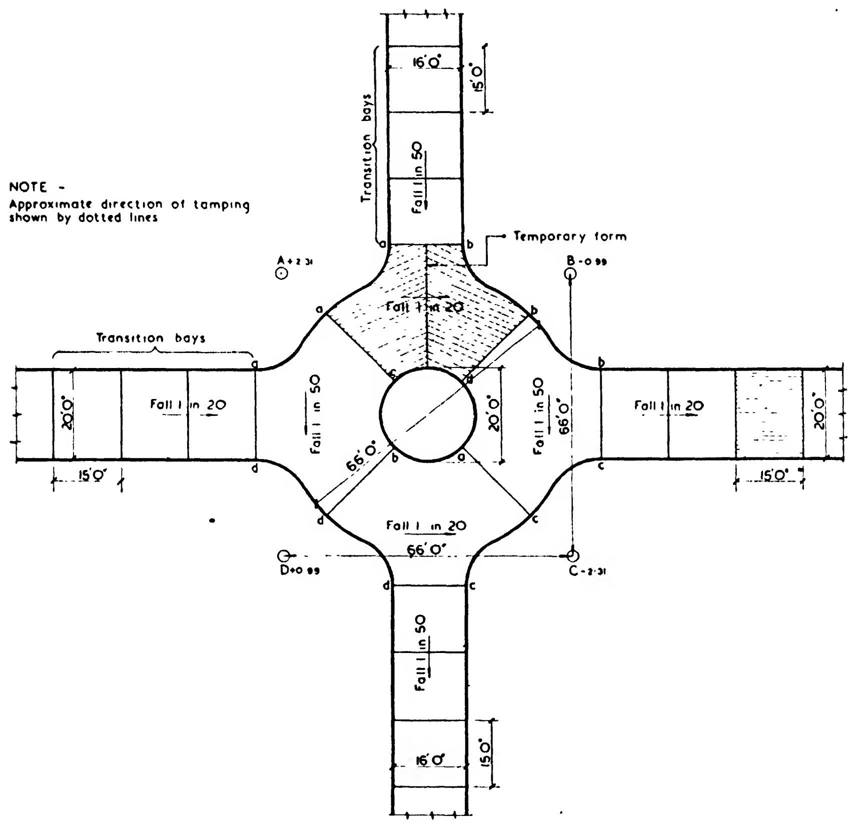


FIG. 81.—ROUNDABOUT AND ISLAND AT CROSS ROADS.

from B to C. Levels were fixed so that the intersection of the lines AC and BD would coincide with the intersection of the two road crowns at the centre of the island. The levels of the four pegs, referred to the crown-intersection as datum, were: A, + 2·31 ft.; B, − 0·99 ft.; C, − 2·31 ft.; and D, + 0·99 ft. The four pegs were sufficient for setting the forms inside the roundabout. The form ab in the diagram was set for line and for the level of the screeding edge by interpolation between A and B. The two forms ac and bd were similarly set from the pegs A and C, the other five forms being fixed in a similar manner.

When the forms were in position the concrete in each large panel could be tamped in any direction with a straight tamper. The approach to the roundabout from any of the intersecting roads passes over three transition bays each 15 ft. long, in which the ordinary camber of the road is gradually changed to a straight cross-fall of 1 in 20 in the case of one road and 1 in 50 in the other.

With a slight alteration the same system can be applied to a circular space without a central island. In such a case a central space, preferably square in shape, would be left and concreted after the four surrounding panels have been completed. This area would be tamped with a slightly cambered tamper working off the surface of the surrounding concrete.

Curves and Superelevation.

Prior to the advent of motor traffic little attention was given to the planning of roads or to the general design and arrangement of curves. The importance of this subject has since been realised and due attention is now given to these points when new road work or re-surfacing is under consideration. Memorandum 575 on "The Lay-out and Construction of Roads" issued by the Ministry of Transport in 1943, contains the following reference to curves and superelevation:

"Curves should normally be laid out as segmental arcs of the largest practicable radius. If the radius of the segmental arc is less than 5,000 ft. the curve should be approached at each end by a transition curve. Where the total length of the curve is not sufficient to permit the introduction of an adequate length of transition as an approach to a segmental arc, the curve should be made transitional throughout. If physical conditions render the use of curves of shorter radius than 1,500 ft. unavoidable, the normal width of each traffic line should be increased by 1 ft., to be increased to 1 ft. 6 in. for each traffic line where the radius is less than 1,000 ft. and to 2 ft. where the radius is less than 500 ft. Such added width should be obtained by widening the carriageway at a uniform rate along the length of the transition curve. In the improvement of existing curves the widening should generally be made on the inside of the curve."

As a rule curves of less radius than 1000 ft. require to be superelevated if adequate provision for fast traffic is to be made. *Table* XVI gives the calculated gradient for different curvatures up to 1000 ft., and for traffic at speeds of 10 to 30

TABLE XVI.—GRADIENTS FOR VARIOUS CURVATURES AND SPEEDS.

Radius (ft.)	10 m.p.h.	15 m.p.h.	20 m.p.h.	25 m.p.h.	30 m.p.h.
25	1 in 3·75				
50	1 in 7·50				
75	1 in 11·25	1 in 5·00			
100	1 in 15·00	1 in 6·66			
150	1 in 22·50	1 in 10·00			
200		1 in 13·33	1 in 7·50		
300		1 in 20·00	1 in 11·50		
400		1 in 26·66	1 in 15·00		
500			1 in 18·75	1 in 12·00	
600			1 in 22·50	1 in 14·50	
700			1 in 26·25	1 in 17·00	1 in 11·66
800			1 in 30·00	1 in 19·25	1 in 13·33
900				1 in 22·00	1 in 15·00
1000				1 in 24·00	1 in 16·66

miles per hour, according to the radius of curve. *Table* XVII gives the superelevation given by the Ministry of Transport in Memorandum No. 575 for general guidance.

The elimination of adverse camber and the attainment of the required superelevation should be obtained by raising the outer above the inner channel of the carriageway at a uniform rate along the length of the transition, from the end of the straight to the commencement of the circular curve where the superelevation should reach its maximum.

TABLE XVII.

Radius in Feet	Superelevation
1200 or less	1 in 14½
1400	1 in 17
1600	1 in 19
1800	1 in 22
2000	1 in 24
2500	1 in 30
3000	1 in 36
3500	1 in 37
4000	1 in 38
4500	1 in 39
5000	1 in 40
5000 to 7500	1 in 40 to 1 in 48, according to nature of surfacing material.
Over 7500	Normal camber or cross fall retained.

A formula which is also in general use is as follows:

$$\text{Superelevation in inch per foot width of road} = 0{\cdot}8 \times \frac{(\text{miles per hour})^2}{\text{radius (ft.) of curve}}.$$

Or, if the curve is measured in degrees:

$$\text{Superelevation in inch per foot width of road} = 0{\cdot}00014 \times \text{degree of curve} \times [\text{velocity (m.p.h.)}]^2$$

A cross-fall of 1 in 12 represents a suitable and safe limit for a radius of 150 ft. or upwards, but in special cases 1 in 10 or even 1 in 8 may be applied to advantage. Cross-falls from 1 in 12 down to 1 in 24 may be used for curves up to and above 1000 ft. radius, always bearing in mind that with such curves there is greater vision and higher speeds are developed with safety.

Where a curve occurs on a level road the speed of the traffic in each direction is similar, and the banking is carried out by a gradual change from the cambered to the superelevated section before reaching the tangent point of the curve. If there is any hesitation in adopting the calculated cross-fall of, say, 1 in 10 or 1 in 12, the slope can be arranged to work up gradually to the greatest value at the middle point of the curve; this enables a maximum centre cross-fall of 1 in 8 to be used if desired without danger of vehicles overturning.

To superelevate a curve on a concrete road which is being laid in half widths (*Fig.* 82), set out points B, F, C, and G to the required levels, and bone between F and G to produce the intermediate kerb levels, also between B and X and C and X, X being the lowest point for surface drainage purposes. The parts AE and DH are cambered in the ordinary way, the levels of points a and d being given. To set the centre form, bone between a and b, b and c, and c and d, and proceed with concreting. Working to these levels will produce the required superelevation and work back to the ordinary camber, no matter what the radius or superelevation required. The change effected is so gradual that it cannot be detected with the eye.

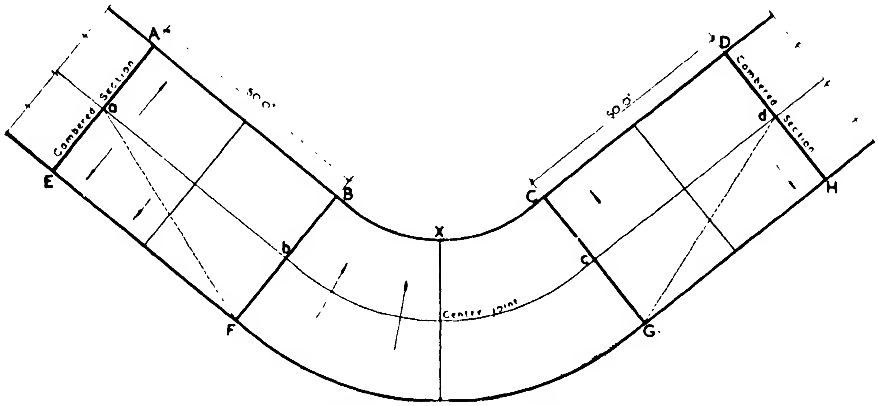


FIG. 82.—SUPERELEVATION OF ROAD LAID IN HALF-WIDTHS.

A method of banking the road surface at forked roads is shown in *Fig.* 83. This is similar to the method described for a curve, because the road surface prior to the fork is cambered in the ordinary way.

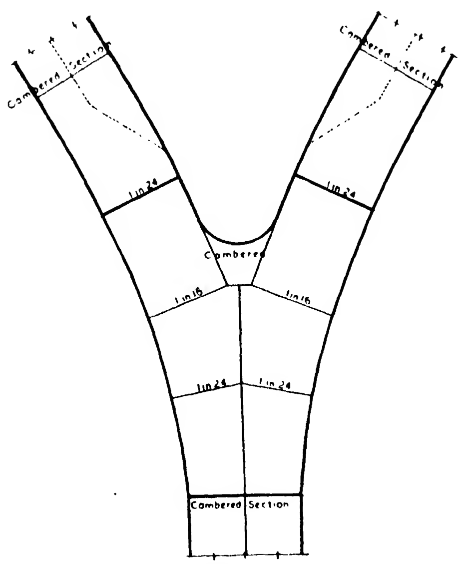


FIG. 83.—SUPERELEVATION AT ROAD JUNCTION.

Hilly roads cause more difficulties than gentle rises, particularly where curves occur on gradients and there are two speeds of traffic to deal with, the slow " up " traffic and the fast " down " traffic ; it is the latter which makes superelevation a necessity. The higher speeds induced by gravity create a tendency for vehicles to cut the corner—this is, however, common to all curves even where superelevation is carried out.

Curves at the foot of a gradient also present a problem by reason of the development of higher and probably variable speeds. It may be desirable in cases of this kind to increase the range of vision in addition to providing superelevation at the curve. A maximum rate of banking would be justified where the down gradient is considerable.

It is important that the road should have a good foundation and wearing surface at the bends. Even where the road is superelevated there may be additional wear due to vehicles travelling above or below the calculated speed for the banking.

Concrete roads are admirably suitable for superelevation as the forms can be set to obtain the varying cross-falls with extreme accuracy, and in addition they provide the foundation and non-skid surface required.

Transition Curves.

Transition curves are introduced between a straight length and a curved portion of a road to avoid a sudden change from a rectilinear to a circular path. The elimination of a sudden change increases safety, avoids discomfort to the passenger, reduces shock on the vehicle, and minimises wear of the road surface. For appearance as well as safety, the centre-line of the road and the kerb lines should follow the natural path of the vehicle, a condition that is complied with if a transition curve is provided not only where a straight length meets a curve, but also when changing from a curved to a straight stretch.

Since the length of a transition curve depends upon the speed with which it is desired to negotiate the bend, it is not possible to design a transition curve that will give safety and comfort at an unlimited speed. Transition curves are essential on main roads, but may be omitted on roads where speeds are normally low.

The radius of a transition curve varies from infinity (that is, a straight line) where it leaves the straight, to equality with the radius of the circular curve where it joins the latter. Normally transition curves are designed between these two extremes as lengths of either a lemniscate or a spiral, which present in practice no pronounced differences.

The transitional portion of a curve provides a convenient length for changing from the normal camber prevailing on the straight length to the superelevation provided on the circular curve. A transition curve is even more essential when the circular curve is not superelevated.

CHAPTER X

COLOURED CONCRETE ROADS

THE use of coloured cement for roads, footpaths, cycle tracks, and similar paving, enables warmer tones to be obtained than that resulting from grey Portland cement.

Coloured concrete roads are generally constructed in two courses, the coloured course, about 2 in. thick, being laid as soon as the base course of ordinary grey concrete has been finished. To obtain the best results the coloured topping should be laid with the least amount of water consistent with workability. The same proportion of cement and the same consistency must be maintained throughout the work, otherwise the colour will be uneven. A shortage of cement or an increase in water content will result in a lighter tone, because a reduction in the cement content means a lower percentage of colouring matter in the mass whilst excess of water may result in extra coloured cement coming to the surface. It is an advantage to use a coloured aggregate such as red quartzite or granite with red Portland cement, and gravel if buff Portland cement is used. It is also advisable before proceeding with the work to lay a trial section of one or two square yards in order to arrive at the best proportions and to obtain an idea of the tone produced.

The construction of a coloured concrete road is similar to that of an uncoloured road with the exception of the curing. Whenever possible separate mixers should be used for the bottom course and the coloured topping and attention given to the cleanliness of the barrows, skips, shovels, etc. The top course should not be overtamped ; the advantage of using a smoothing board for coloured work cannot be over-emphasised. Curing should always be carried out with stout waterproof paper laid on the surface as soon as the moisture sheen has disappeared. The application of moisture to the surface in any form, such as damp canvas or watering, must be avoided since these tend to cause efflorescence and to affect the colour.

Contraction joints should be provided at the same spacing as for ordinary concrete roads. The joints should be sealed with coloured compound that will tone with the surrounding concrete. Since this material is costly compared with ordinary bituminous fillers, it is only used in the top 1 in. of the joint and is heated and poured after removal of a metal capping device temporarily fixed to the filler in the lower portion of the joint.

Exposed Aggregate Surfaces.

A pleasing effect may be obtained by exposing the aggregate in the surface. This result is obtained as follows. Approximately one hour after the surface has been finished with the smoothing board a soft-hair brush is lightly drawn across it to remove laitance. Curing by waterproof paper is immediately commenced, and 12 to 18 hours later, depending upon the temperature and the hardness of the concrete, the surface is uncovered and brushed with a stiff bass broom to remove the cement film from the coarse aggregate. Curing is then immediately resumed.

CHAPTER XI

LABOUR REQUIRED FOR VARIOUS OUTPUTS

THE organisation of the work and the selection of plant to give a satisfactory and economical output of concrete for road works are closely related to the consistency of the concrete to be used, since this largely governs the method to be adopted for the subsequent operations of distribution and compaction of the mixed concrete. Concrete made with a low water-cement ratio is difficult to place and compact by hand, yet both operations can readily be carried out by the use of suitable machines. On the other hand, no advantage is obtained by employing mechanical methods to compact very wet concrete; in fact they will probably do more harm than good. The labour required to distribute and compact by hand, concrete having a slump of ½ in. or less might well be twice that needed for concrete with a slump of 3 in. or more. Machines for spreading and compacting concrete will work faster and give a satisfactory surface finish in less time with a slightly plastic mixture than with one of a "dry" consistency.

Owing to the different circumstances of nearly every contract, such as those concerned with the site and the area available for storing materials, it is impossible to prepare a schedule of labour requirements applicable to every case. The following examples, however, taken from practice, show the number of men employed on batching, mixing, transporting, distributing, and finishing the concrete on recent road works. The labour required for the preparation of the foundation, treatment of the sub-base, erection and removal of side forms, and supervision are not included since these are not directly or entirely connected with concreting operations.

Example No. 1.—Output of 6 to 9 cu. yd. per Hour.

Portable mixer, 14/10 cu. ft. capacity; concrete compacted by hand. The following labour was employed:

	No. of men
Mixer driver	1
Opening cement bags and charging cement into mixer hopper	1
Loading mixer hopper with sand and stone	4
Spreading and levelling concrete	2
Compacting and finishing concrete	2
Finishing joints	1
Curing and miscellaneous	1
Total	12

This arrangement is only suitable when the supplies of aggregate can be delivered behind the mixer and the concrete discharged directly into the work, the mixer being moved forward as the work proceeds. On work of this type the concrete is rarely subject to very strict control and tends to be rather on the wet side since the increased workability saves effort in placing and compacting. With slumps of 3 in. to 4 in., an output of 6 to 7 cu. yd. per hour can be maintained for long periods, whilst for short periods an output of 8 to 9 cu. yd. per hour is possible. Assuming the higher figure in each case, the man-hours required per cubic yard of concrete would be approximately 1·7 and 1·3 respectively, or a mean of 1·5 man-hours per cubic yard. With mixes having slumps of ½ in. to 1 in. these outputs would probably be reduced by 50 per cent., giving a mean of 3 man-hours per cubic yard.

Example No. 2.—Output of 6 cu. yd. per Hour.

This refers to housing site roads constructed in the Midlands by contract in 1945. The concrete was mixed in a portable mixer and transported in wheelbarrows. Distribution was by hand, and the concrete was compacted and finished by vibrators mounted on a tamping board. The labour employed was as follows.

	No. of men
Mixer driver	1
Loading cement into mixer	1
Loading mixer hopper with sand and stone	4
Transporting concrete by wheelbarrow	3
Spreading and levelling	2
Compacting and finishing	2
Finishing joints	1
Curing and miscellaneous	1
Total	15

The average output was about 6 cu. yd. per hour. The slump of the concrete was approximately 1 in. The man-hours per cubic yard were $\frac{15}{6} = 2{\cdot}5$.

Example No. 3.—Output of 40 cu. yd. per Hour.

Central batching and mixing plant with two continuous mixers. The capacity of each mixer was 25 cu. yd. of mixed concrete per hour, and the machines were arranged so that their aggregate hoppers could be loaded by a dragline bucket excavator digging aggregate from a stock pile which was replenished by lorries, a bulldozer being used to push the aggregate up to the bucket when necessary. Cement was delivered in bulk-cement lorries which discharged directly into the cement hoppers over the mixers. The concrete was discharged into hoppers from which it was transported to the site by lorries.

The following labour was employed at the batching and mixing plant:

	No. of men
Dragline driver	1
Bulldozer driver (part time)	1
Mixer drivers	2
Men on cement	2
Labourers dealing with spilt material and general work	2
Lorry drivers (depending on length of haul)	6
Total	14

The concrete was dumped directly on to the prepared ground where it was distributed, compacted, and finished by machine. The following was the labour employed at the site of the work:

	No. of men
Distributing machine driver	1
Compacting and finishing machine driver	1
Labourers attending machines	2
On joints	3
Curing	3
Total	10

A complete cycle of concreting operations occupied an average of 24 minutes. The output varied from 30 to 50 cu. yd. per hour. Assuming an average of 40 cu. yd. per hour, the man-hours per cubic yard (excluding supervision) were:

Batching, mixing, and delivering	$\frac{14}{40} = 0{\cdot}35$
Distributing, compacting, and finishing	$\frac{10}{40} = 0{\cdot}25$
Complete cycle of operations	$\frac{24}{40} = 0{\cdot}60$

Example No. 4.—Output of 30 cu. yd. per Hour.

"Paver" mixer of 1 cu. yd. capacity. The mixer travelled under its own power alongside the strip under construction, moving as concreting proceeded. The materials were proportioned at a central batching plant and discharged into end-tipping lorries divided transversely into compartments each holding one batch. A 5-ton tipping lorry held two batches of one cubic yard each. The number of lorries required depended on the distance between the batching plant and the mixer and ensured the delivery of one batch at intervals of about 1½ minutes. Assuming that six lorries were used, the labour required to batch, mix, and distribute the concrete was approximately as follows.

	No. of men
Elevator or dragline driver	1
Bulldozer driver (part time)	1
Batcher box or weighing-machine operator	1
Men on cement delivered in bulk (6 men required for bag delivery)	2
Lorry drivers	6
Mixer driver	1
Banksman for mixer driver	1
Total	13

Assuming that 10 men are employed on distributing and finishing as in Example No. 3, the total number of men employed is 13 + 10 = 23 exclusive of supervision. The output might reach 45 cu. yd. per hour at peak periods; allowing for delays, a conservative figure of 30 cu. yd. per hour may be taken. The man-hours per cubic yard would then be:

Batching and mixing	$\frac{13}{30} = 0{\cdot}43$
Distributing and finishing	$\frac{10}{30} = 0{\cdot}33$
Complete operation	$\frac{23}{30} = 0{\cdot}77$

The water required by mixers of the paver type may be supplied either by (*a*) A supply pipe laid alongside the road with tees at intervals connected to the tank on the mixer by a flexible hose. The tees should be spaced at such intervals that the least time is lost when the limit of the flexible pipe is reached and a fresh connection is required, or (*b*) Tank lorries bringing water from a standpipe to the mixer. The capacity of the lorries should be about 1000 gallons and a pump provided either on the mixer or the lorry to transfer the water to the supply tank on the mixer.

Example No. 5.—Output of 15 cu. yd. per Hour.

In the construction of the Chichester by-pass road by direct labour in 1938 and 1939, the concrete was proportioned and mixed at a central batching and mixing plant with a 1-cu. yd. mixer, the mixed concrete being transported to the site in lorries. The bins containing the sand and coarse aggregate were fed from stockpiles by a crane with a self-dumping grab. After being proportioned by weight, the sand and coarse aggregate were passed to a fixed hopper where the cement was added by means of a hoist, four bags being used for each batch of the bottom-course concrete and five bags for the top-course mixture. The materials were fed direct into the drum of the mixer and, after being mixed, were discharged into 3-ton side-tipping lorries each containing two 1-yd. batches. The concrete was then hauled to the work and discharged into a trough distributor (see *Fig.* 45).

The following labour was employed at the central batching and mixing plant :

	No. of men
Crane driver	1
Stock piling	2
Unloading cement	2
Mixer driver	1
Total	6

At the site of the work and employed on transport there were :

	No. of men
Lorry drivers	6
Driver of distributing machine	1
Driver of finishing machine	1
Labourers attending machines	5
Preparing and finishing joints	4
Curing	4
Total	21

A normal output in a 9-hour day was 520 ft. of road 11 ft. wide by 8 in. thick, laid in two courses with a single layer of reinforcement (approximately 141 cu. yd. of concrete). The man-hours per cubic yard of concrete were $\frac{243}{141} = 1{\cdot}72$.

Example No. 6.—Output of 10 cu. yd. per Hour.

In the construction of the Caterham by-pass road by direct labour in 1937 and 1938, the concrete was batched and mixed at a central site. The aggregates were delivered by lorries and discharged on to a raised platform from which they were shovelled into timber hoppers whence they were discharged into jubilee skips. The skips and their contents were weighed on a weighbridge before being tipped into the mixer hoppers. Three mixers, each of 14/10 cu. ft. capacity, were used. The concrete was discharged into four three-way 2-ton capacity hydraulic tipping lorries and taken to the work, where it was discharged into a mechanically-operated distributor of the hopper type.

The following labour was employed at the central batching and mixing plant :

	No. of men
Mixer drivers	3
Weighbridge operator	1
Labourers loading aggregate hoppers and skips	4
Labourers unloading cement and weighing half-bags . . .	3
Labourers on skips feeding mixer hoppers	6
Boy controlling water supply to mixer	1
Total . . .	18

At the site of the work and on transport there were employed:

	No. of men
Lorry drivers	4
Driver of distributing machine	1
Driver of vibrating road finishing machine	1
Labourers on joints and finishing sides of bays	5
Labourers unloading lorries into distributor, spreading sand, and laying waterproof paper and reinforcement	3
Total . . .	14

The average output was 350 sq. yd. of 8 in. slab per day of 8 hours. This equals approximately 78 cu. yd. for 256 man-hours, or 3·3 man-hours per cubic yard.

Example No. 7.—Output of 17 cu. yd. per Hour.

This relates to the construction of housing-site roads carried out by contract in 1945. The coarse aggregate was delivered in three sizes, stock piled, and raised by an elevator boom to the storage bins of the central batching plant. The cement was delivered in bags and elevated to storage bins. The mixer was of 1 cu. yd. capacity and all materials were proportioned by weight. The mixed concrete was discharged into jubilee skips and hauled by locomotives to the site.

The following labour was employed in batching, mixing, and delivering concrete:

	No. of men
Moving elevator boom to stockpiles and the delivery chute to appropriate storage bin	1
Controlling weigh-batcher and electrically-operated concrete mixer .	1
Opening cement bags and feeding cement to elevator	2
Loco. drivers	2
Total . . .	6

In placing and finishing the concrete there were employed:

	No. of men
Spreading concrete	8
Driver of vibrating road finishing machine	1
Attending finishing machine (keeping screed clear and feeding to low spots after first passage of machine)	2
Installing joints, dowel bars, etc.	2
Finishing joints	2
Curing	1
Total . . .	16

A normal 8-hour day's output was 168 batches of 0·825 cu. yd. each. This equals 138 cu. yd., or 17 cu. yd. per hour, which is equivalent to 1·27 man-hours per cubic yard. This comparatively low output is mainly due to manual distribution of the concrete; a machine for this work would probably have saved at least six men and decreased the man-hours per cubic yard by about 20 per cent., but would increase the plant costs.

Summary.

These examples indicate that for well-organised work for which mechanical plant is employed for all the concreting operations, the expenditure of man-hours per cubic yard is substantially less than for similar work carried out by manual methods. The introduction of manual labour to replace an operation that can be done by machine increases the man-hours on the concrete without any corresponding increase in output. Although there is a considerable saving of man-hours when machines are used, it must not be overlooked that the plant is expensive. Its employment, therefore, will depend not only upon its probable useful life (generally taken to be about five years) but also upon the volume of concrete for which it can be employed in that period.

The following summarises the man-hours per cubic yard for the foregoing examples.

	Man-hours
Example No. 1.—Machine-mixed concrete placed and finished by hand:	
3-in. to 4-in. slump	1·50
½-in. to 1-in. slump	3·00
,, ,, 2.—Machine mixed. Placed and finished by hand. 1-in. slump	2·50
,, ,, 3.—Central batching and mixing plant with two continuous mixers; concrete transported by lorries and distributed and finished by machine	0·60
,, ,, 4.—Central batching plant and paver mixer with crawler track; concrete distributed with boom-and-bucket distributor and finished by machine	0·77
,, ,, 5.—Central batching and mixing plant; concrete transported by lorries and distributed and finished by machine	1·72
,, ,, 6.—Central batching and mixing plant, concrete transported by lorries and distributed and finished by machine	3·30
,, ,, 7.—Central batching and mixing station; concrete delivered in jubilee skips drawn by loco., distributed by hand, and finished by machine	1·27

CHAPTER XII

MAINTENANCE AND REPAIR

CONCRETE roads have now been in use for a sufficiently long period under all types and conditions of traffic, including the war years when in many districts the traffic was heavier and more abrasive than that for which the roads were designed, for the question of maintenance to be based on experience. In general the roads have stood up well, but minor faults have developed which if attended to at once would save greater expense later on. It is unfortunate, however, that in many cases it has not been possible to undertake maintenance work in a systematic manner. There are many concrete roads ten or more years old on which nothing has been done, but had minor faults been repaired and a little attention given to the joints the appearance of the surface would have been improved and the road assured of a much longer life.

Faults in a concrete road are due to a variety of causes. Serious cracking may be due to a weak foundation or a badly-compacted sub-base, to too thin a slab, to overloading, or to fatigue of the concrete in bending. Faults in the surface (depressions, spalling at joints, etc.) are mainly due to the use of unsuitable aggregate, to insufficient curing, or to frost. Ravelling and crushing at joints are invariably due to faulty workmanship or unevenness in the level of the joints. Joints may also suffer damage due to failure to give attention to the filler. During hot weather some fillers are partly squeezed out and portions broken off and removed by traffic. In cold weather the slab contracts and the joint is no longer completely filled. This results in damage to the edges by the impact of traffic and to softening of the foundation by surface-water passing through and causing transverse cracks and corner breaks near the joint. The best time for an inspection is in late autumn when cold weather has started but before severe frosts occur. A systematic overhaul involves little expenditure and should be carried out regularly.

The maintenance cost over ten years has been as low as $\frac{1}{8}d.$ per square yard per annum over many miles of concrete road. Even for a road carrying heavy traffic, such as the Chelsea Embankment carrying over 15,000 tons a day at considerable speed, the total maintenance cost during the first eight years was approximately *2d.* a square yard and now, after nearly twenty years, the general state of the road remains practically unimpaired.

The organisation required for maintenance is largely determined by the area of the work. It should be under the control of one man, assisted by three or more specially chosen for the work. Experience will soon add to the efficiency of the men, and thereby reduce maintenance costs to a minimum.

Plant Required.

The plant mostly required consists of shovels, brooms, steel rakes with the ends slightly curved for raking out joints, receptacles for heating joint-sealing material, pouring cans, and wedges or chisels. For making openings to reach service mains heavier equipment will be required, but such work is not strictly maintenance and is referred to later. For reinstating the concrete slab one or two gauge boxes will be required, together with tampers, straightedges, edge rounding tools, and watering-cans. In country districts a water cart may be included; in such districts a light lorry to transport the men, tools, and materials will be useful, and a lorry equipped with these tools should be maintained by authorities responsible for concrete roads when the mileage is extensive.

Materials Required.

The materials required are aggregates, cement, water, reinforcement, and material for filling and sealing the joints. The cement should be rapid-hardening Portland cement or, for very urgent work, high-alumina cement. The other materials should be up to the standard required for the production of High-Grade concrete. The joint filler should be of the non-extruding type and the joint sealed with a good sealing compound. Cold emulsions are suitable for filling fine cracks and for protecting concrete patches from abrasion during the first two or three weeks after they have been laid.

Joints and Cracks.

The maintenance of joints may involve either or both of the following operations: (1) Repair to damaged concrete at the edges; (2) Reinstatement of the filler. Repairing the concrete at joints is dealt with later under "Openings, Trenches, etc." All filling material that has been squeezed out should be removed. The top 2 in. of the joint should be thoroughly cleaned out by metal scrapers, wire brushes, or similar tools. If the filler is a bituminous material the concrete, which must be clean and dry, should be painted with creosote. The molten filler is then poured in, only sufficient being used to fill the joint level with the road surface. While the filler is still liquid it should be covered with coarse dry sand. The filler should not be heated above the temperature recommended by the makers since this may drive off the volatile oils and cause the material to become brittle when cool. On the other hand, too low a temperature may cause the filler to solidify too quickly and prevent the joint being completely filled.

Fine cracks do little harm and are best left alone. If the crack is wide enough to admit grit and water, all dirt and loose particles should be removed by a wire brush and the crack given one or two coats of sealing material. Wide or deep cracks may have to be filled a second time. Sealing material should not be poured in a wide band along the edge of the crack or joint; it does no good there, wastes material, and is unsightly. It is best to lay a thin batten on each side of the crack and about 1 in. away from it and pour the filler between the battens, thus ensuring a reasonably straight edge. This method is particularly useful for filling joints.

Surface Repairs.

For a permanent and unnoticeable repair the most satisfactory method is to cut out and remove the damaged or unsound concrete to a depth of about 1½ in. The edges should be trimmed square to the surface and the concrete thoroughly cleaned with a wire brush, using plenty of water so that the edges are free from dust and loose particles. No water should be left in the hole.

A slurry of neat cement—of the consistency of thick cream—is applied to the edges and worked well into the interstices. The hole should then be filled with new concrete, 1 : 2 : 4 nominal mix, composed of similar materials to those used for the original work provided these were of good quality. The water content must be as low as possible and mixing should therefore be very thorough. The concrete must be well consolidated into all corners and against the bottom and sides of the hole; it is advisable to place the new concrete about $\frac{1}{4}$ in. proud of the finished surface to allow for shrinkage and settlement. After an interval of 40 to 60 minutes—depending upon the temperature and the consistency of the concrete—tamping should be repeated to ensure thorough compaction and a close bond with the old work. This second tamping should be delayed as long as possible provided it is possible to produce a satisfactory finish of proper contour and texture. The surface should be checked with a straightedge to ensure that it is in line with the old paving and free from surface irregularities. The aim is to produce a patch which will match the surrounding concrete and soon become indistinguishable.

The new concrete should be well cured and closed to traffic for the period recommended on page 60. These periods may be reduced to 24 hours by using high-alumina cement provided special precautions are taken. While high-alumina cement concrete will bond satisfactorily to matured Portland cement concrete, neither must be allowed to come in contact with the other when newly mixed. For a patch made with high-alumina cement the grout used for painting the exposed surfaces of the old work must also be made with high-alumina cement. A suitable nominal mix for high-alumina cement concrete is 1 cu. ft. (90 lb.) of cement, $2\frac{1}{2}$ cu. ft. of damp sand $\frac{3}{16}$ in. down, and 4 cu. ft. of stone of a maximum size of $\frac{3}{4}$ in. The quantity of water should be just sufficient to make the mixture, after thorough mixing, freely plastic. The water content should be at the rate of $5\frac{1}{2}$ gallons to each 1 cwt. of cement; less than $4\frac{1}{2}$ gallons per cwt. of cement should never be used. Very thorough curing will be required; the patch should be frequently sprayed with water as soon as this can be done without damaging the surface, and continued until the concrete is 24 hours old. Alternatively, the concrete may be covered with coco-nut matting or two or three layers of sacking well soaked with water. In cold weather patches can be carried out with Portland cement to which calcium chloride has been added (see page 60).

Openings, Trenches, etc.

Openings in concrete roads are not difficult and expensive to reinstate. With ordinary care repairs can be made economically which are not different in appearance from the original concrete or inferior to it in strength, provided careful consideration has been given to the preparation of the area to be patched and the proportioning, placing, finishing, and curing of the concrete. Since patching is usually done without closing the road to traffic, arrangements must be made for handling traffic and providing protection to the workers and to the patch during the curing period.

Where concrete has been removed to obtain access to services or trenches dug in the road foundation, care must be taken in filling the trench to make it equal in bearing value to the adjacent ground.

In cases of roads other than those carrying light traffic the slab should be cut back at least 6 in. beyond the side of the trench so that the replaced section bears on the original undisturbed foundation (see *Fig.* 84). The filling should be placed in layers of not more than 9 in., and each layer thoroughly compacted. If the slab is being reinstated because it has fractured, the foundation should be examined since capillary rise of water or other conditions may have caused softening of the foundation and contributed to cause the break. In such cases it may be worth while to replace affected areas with a selected material having a satisfactory bearing capacity, compacting it in lifts of suitable thickness up

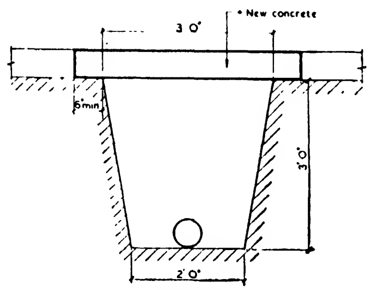


FIG. 84.—REINSTATEMENT OVER A TRENCH.

to sub-base level; in other words, the ground should be treated in much the same manner as new work. The sub-base should be either clinker or dry sand of the same consolidated thickness as that under the original slab, and damped before placing the concrete. The face of the old concrete should be carefully dressed so that the top 1½ in. is vertical and all loose or fractured material removed. Below the top 1½ in. the concrete should be left rough and slightly inclined towards the centre of the opening. The new concrete may then be placed, using the same care in cleaning and grouting the old surface as already described for shallow surface patches.

Concrete Mixtures for Repair Work.

The proportions of cement and aggregate and the amount of mixing water must be selected to give concrete of the desired strength and durability. Generally, 1 part of cement to 5 parts by weight of mixed aggregate will be satisfactory with a water-cement ratio of approximately 0·50 (5½ gallons of water including free moisture in the aggregate per cwt. of cement) to give a maximum slump of 1½ in. *Table* XVIII gives suggested proportions for concrete to be cured for 1, 3, or 7 days before it is used by traffic. These quantities are based on well-graded natural sand and gravel graded from 1½ in. to 3/16 in. The relative weights of fine and coarse aggregate may require adjustment to ensure satisfactory workability. For broken stone graded from 2 in. to 3/16 in. the quantities in the table should be increased as follows: Cement, 5 per cent.; sand, ½ cu. ft.; stone, 1 cu. ft.

Mixing and Placing.

To ensure accuracy and uniformity of the concrete the cement and aggregate should be measured by weight. The mixing water should be measured in a receptacle capable of giving accurate measurement to one-quarter of a gallon.

TABLE XVIII.—PROPORTIONS OF MATERIALS FOR PATCHES.

Type of cement	Quantities per cubic yard of finished concrete	Approximate mix by volume	Quantities per cwt. bag of cement		
			Water (gal.)	Dry sand (lb.)	Gravel (lb.)
When patch is to carry traffic after curing for 24 hours.					
Rapid-hardening	Cement 756 lb.	1			
	Sand 11½ cu. ft.	1⅖	4¾	144	300
	Gravel 19½ ,, ,,	2⅓			
Rapid-hardening Portland with calcium chloride	Cement 612 lb.	1			
	Sand 13 cu. ft.	2	6	190	390
	Gravel 19½ ,, ,,	3			
When patch is to carry traffic after curing for 3 days.					
Ordinary Portland cement	Cement 756 lb.	1			
	Sand 11½ cu. ft.	1⅖	4¾	144	300
	Gravel 19½ ,, ,,	2⅓			
Ordinary Portland with calcium chloride	Cement 670 lb.	1			
	Sand 10½ cu. ft.	1½	5¾	180	360
	Gravel 21 ,, ,,	3			
Rapid-hardening Portland	Cement 530 lb.	1			
	Sand 12 cu. ft.	2	7	240	480
	Gravel 23½ ,, ,,	4			
Rapid-hardening Portland with calcium chloride	Cement 470 lb.	1			
	Sand 12 cu. ft.	2⅓	7¾	270	550
	Gravel 22 ,, ,,	4¼			
When patch is to carry traffic after curing for 7 days.					
Ordinary Portland	Cement 530 lb.	1			
	Sand 12 cu. ft.	2	7	240	480
	Gravel 23½ ,, ,,	4			
Rapid-hardening Portland	Cement 470 lb.	1			
	Sand 12 cu. ft.	2⅓	7¾	270	550
	Gravel 22 ,, ,,	4¼			

These weights are based on a well-graded natural sand and gravel graded from 1½ in. to $\frac{3}{16}$ in. The weights of fine and coarse aggregate may require adjustment to ensure suitable workability.

If measurement of the materials by volume is unavoidable, a bag of cement weighing 112 lb. may be taken to contain 1¼ cu. ft. and consideration must be given to the bulking of the sand (see page 66). The concrete should be machine mixed for not less than one minute after all the materials are in the drum, and careful attention must be paid to subsequent operations.

Design.

The shape and dimensions of a portion of a slab to be reinstated depend on its position. Its thickness will be determined largely by the condition of the foundation and the weight and volume of the traffic ; for normal conditions there is no necessity to increase the depth beyond that of the slab.

If the break is in one half-width of the carriageway and extends from the edge to the centre joint, a half-width patch is necessary. *Figs.* 85 to 88 give suggested dimensions for patches in various positions. Patches that are to extend the full width of the slab must be laid in half widths if traffic is to be maintained. The longitudinal joint should be kept as near as possible in the same line as before. In order that the new concrete should not bond with the old concrete in the adjoining traffic line it is advisable to give the exposed face of the longitudinal joint one or two coats of tar; alternatively a thin strip of expansion joint material will serve the same purpose and prevent transmission of vibration to the new concrete whilst it is setting and hardening.

For square patches under 16 sq. ft. in area reinforcement is unnecessary; rectangular patches of the dimensions shown in *Figs.* 85 to 88 should be reinforced with steel fabric, or mild steel bars securely wired together, weighing about 7 lb. per square yard. It is advisable to remove any reinforcement to give better

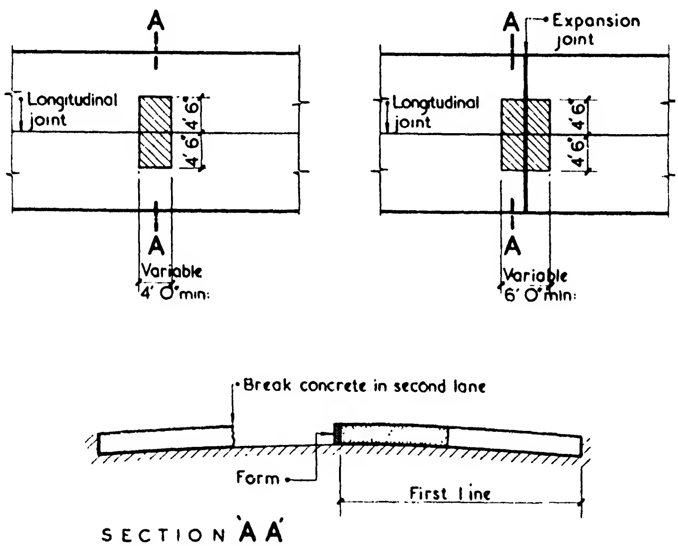


FIG. 85.

access to the foundation and to permit satisfactory preparation of the sub-base, and also to facilitate the placing and compacting of the concrete. If the new reinforcement is required to be continuous with that in the slab, a length of the latter should remain to provide a lap of at least 40 diameters with the new reinforcement. Reinforcement projecting from the damaged slab should be kept in a horizontal position and not bent upwards or out of line, as this may spall or crack the concrete under the bars. The new reinforcement should be secured to the old by wiring or welding. The base of the slab adjacent to the portion removed should be examined to see that concrete under the reinforcement is free from cracks and that spalling has not occurred.

Undercutting the existing slab in order to support its edges with new concrete is not recommended. Not only is it difficult to ensure that the underside of the existing slab is completely exposed, but it is also difficult completely to fill the space under the slab with properly-compacted concrete.

Depressions caused by settlement, such as might occur on an insufficiently-compacted embankment or road widening on new ground, may be corrected by pumping under pressure a mixture of liquid soil and cement between the base of the slab and the sub-base. Holes about 2 in. in diameter and 5 ft. to 10 ft. apart are drilled in the slab to be raised. Sand or soil is mixed with enough

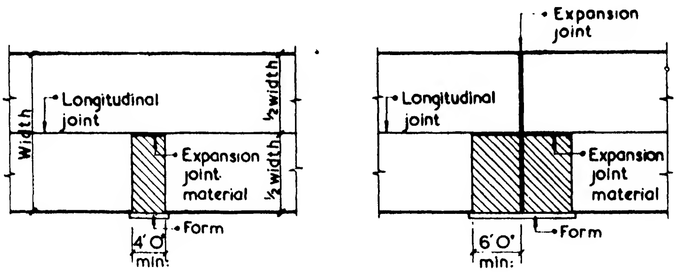


FIG. 86.

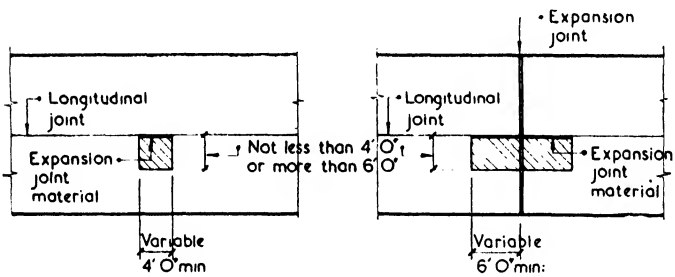


FIG. 87.

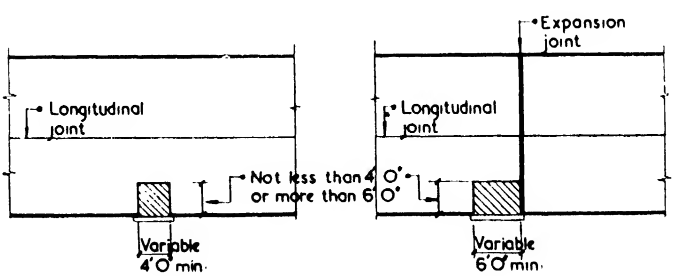


FIG. 88.

cement and water to produce a grout that will just flow under slight pressure; 90 lb. of cement to each cubic yard of sand or soil helps the mixture to set quickly with very little shrinkage. The mixture is pumped under the slab through a pressure hose inserted in the drilled holes and the slab raised evenly by pumping a little in one hole then moving the hose to other holes in rotation until the desired elevation is secured.

Slippery Surfaces.

Occasionally a concrete road that has been given too smooth a finish is polished by traffic so that when wet it is likely to become slippery. A suitable treatment consists of one or more applications of diluted commercial hydrochloric acid (specific gravity 1·11) applied at the rate of 0·03 to 0·30 gallon per square yard according to the degree of roughness required. The acid is poured on to the road surface from rubber or wooden buckets and evenly distributed by means of soft brooms. After an interval of about half an hour the spent acid is removed by spray from a water cart, and bass brooms are used or other means adopted to remove the acid. Any weak acid remaining in the washed-off liquid should be neutralised by placing a quantity of washing soda in each gulley pot. Details of the cost of this treatment, surface texture after treatment, and other data are contained in the Ministry of Transport Report for 1938–39 [Experimental Work on Highways (Technical) Committee].

CHAPTER XIII

CONCRETE HAUNCHES

THE most vulnerable and probably the most important part of a macadamised road is the haunch, which acts as an abutment to the cambered carriageway. Haunches are subjected to continuous and frequently severe lateral thrusts from vehicles, and have to resist the tendency for the carriageway to flatten and spread towards the verges.

In widening and strengthening existing roads the problem has been partially solved in the past by hand pitching reinforced with quarry waste and consolidation by a heavy roller, but haunches constructed in this manner, even if well and carefully made, are not strong enough to resist for any length of time the lateral

FIG. 89.—CONCRETE HAUNCHES USED AS A RUNNING SURFACE, NORTHAMPTONSHIRE.

thrust caused by heavy loads. The material is satisfactory, but hand-packed pitching lacks internal cohesion, contains a high percentage of voids, and is rarely capable of resisting the severe stresses mentioned. In some instances hardcore has been found satisfactory for a time, but a soft foundation does not permit the hardcore to remain consolidated and in time it absorbs the superimposed material. Repeated surfacing, making-up soft and low sides, and continuous filling of pot-holes are not permanent cures, and the sum of their costs exceeds that of a more permanent construction.

Concrete haunching (*Figs.* 89, 90, and 91) compares favourably in cost with the initial cost of hand-packed hardcore, etc., but is superior on account of its long life and stability, and the more uniform distribution of loads attained. If correctly laid there should be no recurring troubles. An advantage of exposed haunching is that of increased visibility. After dark and during fog the concrete haunch provides a useful traffic guide and makes a sharp contrast to the darker

FIG. 90.—CONCRETE HAUNCHES, 5 FT. WIDE BY 6 IN. THICK, ON PORTADOWN-ARMAGH TRUNK ROAD.

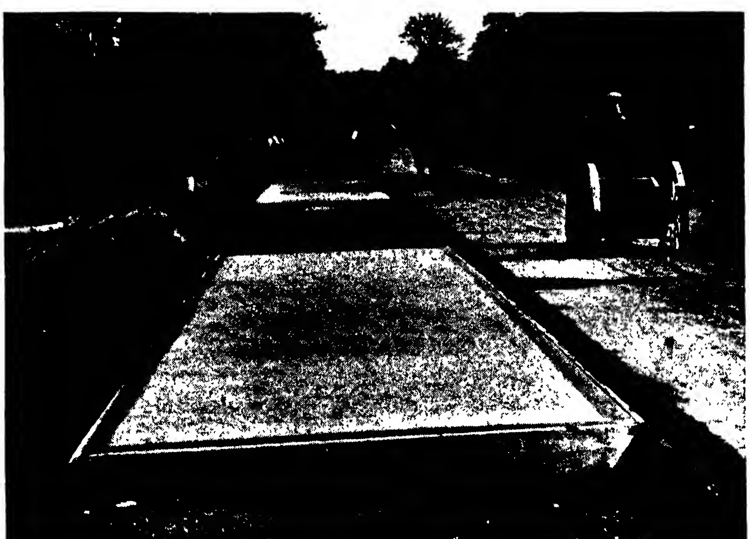


FIG. 91.—CONCRETE HAUNCHES UNDER CONSTRUCTION IN SURREY.

portion of the carriageway. This is particularly valuable when pedestrians use the road as a pathway.

The design of concrete haunching is governed by local conditions, but may be considered under one of the following headings: (1) new road work, (2) widening an existing road on fresh ground, (3) strengthening an existing road having weak and low sides, and (4) strengthening or widening roads in low-lying or marshy areas.

Haunches in New Road Work.

Haunches in this case mostly consist of mass concrete laid to form the foundation for kerbs, and laid sufficiently deep to act as an abutment to the carriageway (*Fig.* 92). On embankments or where the new road is flanked by ditches or low-lying ground, the haunch should be sufficiently deep to ensure that the resultant of the forces acting on the abutment passes well below the surface of the surrounding ground (*Fig.* 93). It should also be wide enough to give substantial support to the shoulders of the road for a distance of not less than 3 ft. from the face of the kerb.

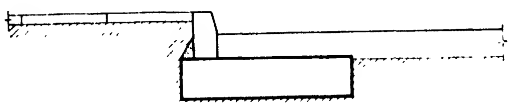


FIG. 92.—HAUNCHING TO NEW ROAD.

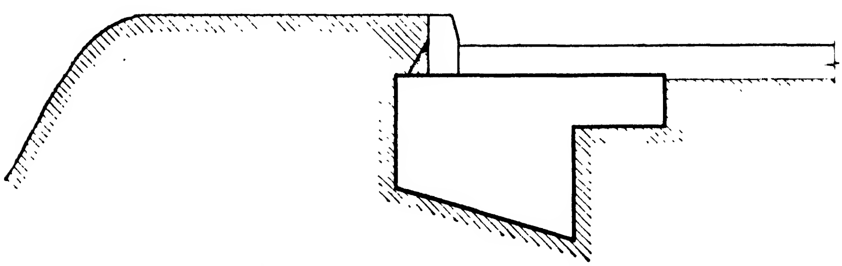


FIG. 93.—HAUNCHING TO NEW ROAD ON EMBANKMENT.

Haunches in the Widening of an Existing Road.

This generally requires a haunch on one or both sides. As a rule the area included in the widening is not consolidated and varies from agricultural land to ordinary filling. In rural districts it generally includes long lengths of open road drains, ditches, etc., which have to be filled and consolidated. For this reason the haunches should be of sufficient width and strength to ensure that the new foundation will be as free from settlement as the old, and therefore not stressed beyond its safe bearing capacity. In complying with these conditions a concrete haunch acts as a raft, bridging over weak places and providing a more uniform distribution of the live loads on the foundation.

Concrete so used may at little, if any, extra cost be constructed to provide both haunch and running surface by bringing the haunch up to the level of the remainder of the carriageway, since there is no necessity to treat the concrete surface or to surface it with other materials. The uncovered concrete area may be used by traffic, which provides visibility at night and can be left to any degree of roughness required. This construction is shown in *Fig.* 94. It is the usual practice to lay the running surface monolithic with the haunch, the latter being composed of concrete in the proportions of about 1 : 2½ : 5 and the surface with 1½ in. to 2 in. of granite or other hard crushed stone concrete in the proportions of approximately 1 : 1½ : 3. Should the new road surface be of either bituminous or asphaltic material it is advisable to lay this so that its finished level is slightly

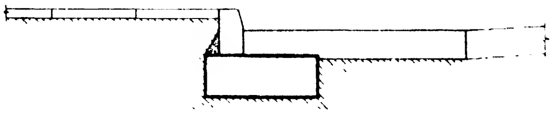


FIG. 94.—HAUNCHING LEVEL WITH CARRIAGEWAY.

above that of the concrete haunching. It is essential to keep the macadam " proud " in order to protect the edges of the concrete haunches. The difference of level should be at least ½ in., as traffic continues to consolidate the tar macadam and eventually the levels become more nearly equal.

Haunches in the Strengthening of an Existing Road.

To buttress an existing road within its own boundaries is a different problem, since the boundaries may consist of ditches, the banks of a stream, embankments, or cuttings. Where the edge falls away sharply the haunches should prevent

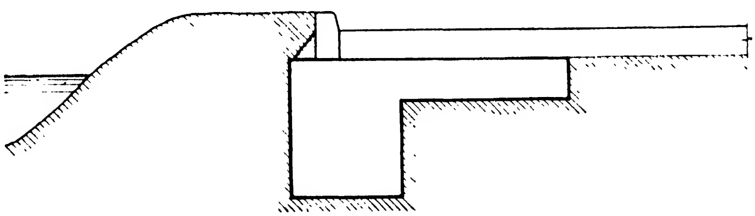


FIG. 95.—HAUNCHING AS BUTTRESS BESIDE STREAM.

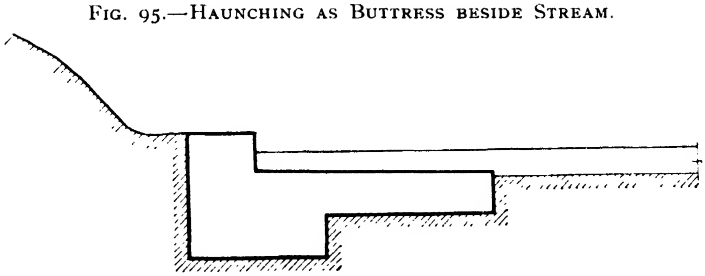


FIG. 96.—HAUNCHING AS BUTTRESS IN CUTTING.

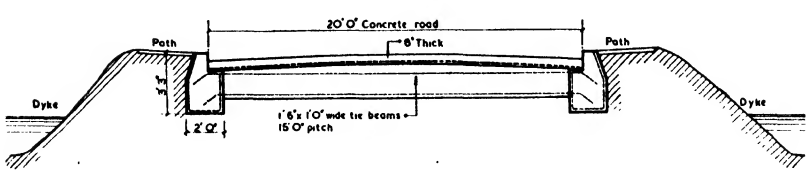


FIG. 97.—HAUNCHES TO STRENGTHEN AN EXISTING ROAD.

any severe lateral pressure being transmitted to the bank (*Figs.* 95 and 96). It may be necessary to tie the haunches together transversely by reinforced concrete tie beams as in *Fig.* 97.

In some districts a suitable properly screened crushed aggregate is not obtainable although a considerable quantity of good stone suitable for hand-packed foundations is available. The engineer may wish to avail himself of this material and can obtain a result not far removed from that attained with concrete. The large stones are placed in position roughly as for hand-packed work and then, after wetting the stone, the voids are filled with 1 : 4 concrete ; the mass thus formed will be more rigid than hand-packed work and cost very little, if any, more. The size of the aggregate used depends on the size of the voids, but probably the maximum will be ¾-in. An alternative method is to fill the voids with a cement-and-sand grout mixed in the proportions of 1 cwt. of cement to 3 cu. ft. of dry sand (3½ cu. ft. damp) with 7 gall. to 8 gall. of water, depending upon the coarseness of the sand and the fluidity required (see Chapter XV, Cement Grouted Roads).

CHAPTER XIV

CONCRETE FOUNDATIONS

The differences between the requirements of a concrete foundation and those of an all-concrete road are that the foundation is not subjected to the same variations of atmospheric conditions and is not required to withstand abrasion. Freedom from abrasion permits the use of aggregates that would not be suitable for a wearing surface. Whereas a hard aggregate is desirable for the latter, a softer and smoother aggregate may be suitable for foundations; otherwise there should be no difference between the two concretes. Concrete for foundation work should have a high compressive strength and have hardened fully before the wearing surface is superimposed. For this reason the use of rapid-hardening Portland cement is common.

The type of foundation required is the same for asphaltic and bituminous carpets, stone setts, and wood blocks; in most cases the same thickness of concrete is provided for all three, while a slightly less thickness is generally used when the surface is to be sett paving. In all cases care must be taken in the preparation and consolidation of the formation, drainage should be attended to where necessary, hardcore rolled in at spots that show signs of softness, and if it is clay the whole surface should be covered with clean well-burnt clinker from 4 in. to 6 in. thick after consolidation.

The thickness of the concrete varies from 6 in. to 10 in., and a single layer of reinforcement, preferably of square mesh and weighing about 7 lb. per square yard, is generally used. Heavier or double reinforcement is used where the soundness of the formation is questionable. In some cases 12 in. of plain concrete has been used in place of a thinner layer of reinforced concrete. Where steel is readily obtainable the thinner reinforced concrete slab is the cheaper, but in countries where steel is expensive the thicker plain concrete slab is favoured.

In Britain the most common types of road foundation are hand pitching and concrete.

Pitched Foundations.

A good pitched foundation is composed of flat stones laid on edge on a well cambered base and firmly wedged against one another by hammering smaller pieces into the gaps between the stones, so that the whole forms a rigid mass somewhat akin to a dry rubble arch. Its strength lies in the arch action produced under load, the thrust being taken by haunching at each side of the carriageway. This foundation served its purpose when the weight of vehicles seldom exceeded a few tons and the speed was not more than ten miles per hour. The effect of modern traffic was either to flatten the crown or to create a thrust on the abutments which the latter were unable to withstand. This is indicated in many country roads by the flattening of the crown and the displacement of the kerbs. An old pitched and well-consolidated foundation can, however, often be saved and made fit for heavy traffic by the construction of substantial concrete haunches as described in Chapter XIII. The haunching should be not less than 2 ft. wide and strong enough to carry the maximum wheel load specified by the Ministry of Transport.

Concrete Foundations.

With a pitched or hardcore foundation the distribution of concentrated loads is only a fraction of that obtained with concrete. Concrete road foundations have the following additional advantages: A good riding surface can be more easily made; the thickness of the carpet can be reduced with consequent economy; rapid construction is possible and, provided that skilled supervision is available, skilled labour is not required; it is practically everlasting and will not spread or distort under concentrated traffic; it protects pipes, mains, and other services; it can be opened up and replaced without difficulty; it is cheaper to lay a carpet on concrete than on a rubble foundation, and the carpet will last longer and require less maintenance; it will keep kerbs in line and level; it can be laid as a raft on ground such as peat bog, marshy ground, or fen-land. For heavy traffic a concrete foundation is essential if smooth running is to be assured.

DESIGN.—The thickness of the concrete and the amount and position of reinforcement are mainly determined by the weight of traffic to be carried and the nature and bearing capacity of the sub-base. The principles used in the design and construction of an all-concrete road apply to the design of foundations. It is not usual to make any allowance for the strength of the superimposed carpet or paving. A 1 : 2½ : 4 mix is recommended if the covering is to be asphalt, tar macadam, or stone setts, and a 1 : 3 : 5 mix if the surface is to be wood blocks.

Experiments carried out by the Ministry of Transport showed that a well-made concrete slab, 6 in. thick, composed of a 1 : 2 : 4 mix, and suitably reinforced, is capable on a good sub-base of carrying heavy and fast traffic with little or no maintenance for many years. Where wood blocks, setts, or asphalt is placed on the concrete foundation it is reasonable to apply the recommendations for the thickness of an all-concrete road to concrete foundations, as the surfacings are not intended to resist stresses set up by traffic. A safe general rule for thickness is: Private streets and suburban roads, 6 in.; roads carrying up to 5,000 tons of traffic per day, 8 in.; 5,000 to 10,000 tons per day, 9 in.; over 10,000 tons per day, 10 in. to 12 in.

Reinforcement should be used where the sub-base is soft or where the road crosses trench excavations. Although a concrete foundation is not always exposed to the same atmospheric conditions as an all-concrete road, the concrete will shrink when setting, and before the carpet is laid it will expand with absorption of moisture; it will also be affected by changes of temperature. The provision of joints, preferably contraction joints, minimises the risk of cracking and eliminates the danger of bursts. Such joints should be spaced and formed as for all-concrete roads. The joints should be at fairly close intervals, as excessive movement of the slab at widely-spaced joints may damage the superimposed surface. It is better to have slabs 20 ft. in length separated by ¼-in. joints than 100-ft. slabs with ¾-in. joints. It is common to provide for contraction by concreting alternate bays, each bay being 12 ft. to 14 ft. in length; with this method the movement at each joint is so little that it does not affect the surfacing. It is also possible that contraction during hardening is greater than any expansion that might occur from temperature changes, and that therefore there is no danger of a burst occurring. In the case of wood-block, tar macadam, or asphalt surfacing 3 in. thick it has been claimed that it is an advantage if the concrete be laid without joints.

On bad ground it is essential to prevent vertical movement between adjoining slabs by the use of dowel bars in the joints or by slabs under the joints. The dowel bars should be 2 ft. to 3 ft. long, 1 in. in diameter, and at 15-in. centres in the middle third of the slab. One-half of the bar should be embedded in one slab and the other half should be free to move in the adjoining slab. The concrete is thus free to expand and contract, but the bars will prevent any vertical movement at the ends of the slabs and will assist to transfer the load of a vehicle from one slab to the next before the vehicle has passed over the joint.

SURFACE FINISH.—Each type of surfacing requires special consideration, and the following notes indicate general practice. Whatever surfacing is used the concrete should be finished to correct camber and cross falls, and attention paid to the level at the channels. The carpet should be of uniform thickness, and this is possible only if the foundation is finished to the correct shape.

For an asphalt carpet the surface of the concrete should have a reasonable degree of rugosity such as a spade finish, but it is possible to superimpose asphalt on a smooth concrete surface previously used for other surfacings. In the case of cold or low temperature asphalt, the concrete is sometimes treated with an emulsion before the asphalt is laid, and it is therefore important that if the concrete surface is ridged the ridges do not exceed $\frac{1}{8}$ in. in height, as the emulsion would be held in the hollows between the ridges and tend to flux the asphalt. An asphalt carpet may be laid 24 hours after the concrete is placed if rapid-hardening Portland cement is used, or four or five days after in the case of concrete made with ordinary Portland cement.

For stone setts the finish of the foundation is not very important as the setts are bedded on $\frac{1}{2}$ in. to $1\frac{1}{2}$ in. of sand or ashes ; a spade finish suffices. The layer of sand should be carefully culled and well rammed. The joints between the setts should not exceed $\frac{1}{2}$ in. and are filled by spreading $\frac{1}{4}$ in. granite chippings over the work and sweeping them about until the joints are as nearly full as possible ; the chippings are well rammed and the joints filled with bituminous grout.

For a tar-macadam carpet a rough concrete surface is preferred but is not essential. Thus it is possible to superimpose tar-macadam on a smooth surface previously used for other surfacings. The period that must elapse between placing the concrete and the surfacing is two to three days if rapid-hardening Portland cement is used or seven to ten days if ordinary Portland cement is used.

For wood-block paving a concrete foundation is essential. It is customary to lay the blocks on the foundation without any intermediate coating of bitumen or similar material.

The practice of placing a topping on a rough concrete base (after the latter has hardened) to achieve a smooth finish has been abandoned, due to failures through lack of adhesion between the topping and the concrete. Heavy traffic frequently caused the topping to be pulverized. The concrete should be brought to a smooth surface and to exact levels and cross sections. If necessary a somewhat finer concrete may be used in the surface, but it must be laid at the same time as the rest of the slab and be homogeneous with it. The concrete should be screeded off with a straightedge and carefully checked for any irregularities or differences of level.

Where a road is to be resurfaced a bituminous binder should be used before applying an asphalt topping. If stone setts are to be used on an existing concrete foundation it is usual to remove the top to a depth of 1½ in. or so and level the surface with a mortar composed of 1 part of cement to 4 parts of coarse sand and finish it with a float. When it is desired to raise the level of an old concrete foundation to take a carpet of tar-macadam, the additional thickness may be made up with old macadam or similar material. When wood blocks are to be used the top of the concrete should be removed and levelled with at least 3 in. thickness of a mixture of 1 part cement, 1 part sand, and 2 parts of ⅛-in. granite chippings.

CHAPTER XV

CEMENT-GROUTED ROADS

THE construction of road surfaces by the application of cement-sand grout to broken stone, chalk, hardcore, gravel, and similar material was first experimented with on a large scale in America in 1933, and has since been fairly extensively used, particularly in the United States and the British Dominions. Successful penetration of grout into a mass of broken stone or gravel depends largely upon the use of a mixture that will flow freely without segregation, and this is influenced by the fineness of the sand, the size and shape of the voids between the coarse aggregate particles, and the cement and water content. Coarse aggregate between 1 in. and 2½ in. is recommended, of which not more than 5 per cent. should pass a ¾-in. sieve.

The Grout.

A suitable mix for the grout is 112 lb. of Portland cement to 224 lb. of sand. Just enough water is added—usually about 7 to 7½ gallons per bag of cement, including moisture in the sand—to make a grout that will flow readily to the bottom of the stone and fill all the voids. Some of the mixing water is absorbed by the sub-base, some is lost by evaporation, and some, as free water, flows ahead of the grouting operations. The water that remains in the slab after consolidation determines the strength of the concrete.

The quantity of water necessary for a grout of suitable fluidity is determined by trial mixes. Stiff grout does not penetrate well, and if the water content is too high there is danger of segregation of the sand, especially if a coarse sand is used. The correct fluidity can be measured by means of a flow cone, an apparatus consisting of a round metal funnel of the dimensions shown in *Fig.* 98 and having a capacity of 221 cu. in.

Sand may be used as delivered but better and more accurate results will be obtained if the sand is weighed and proportioned for test purposes in a saturated surface-dry condition. For this purpose the sand is soaked in water for at least one hour and then drained and dried until all signs of moisture disappear from the surface of the particles. The container must not be allowed to get red hot so that the sand is burned.

For a 1 : 2 mix by weight, 5·3 lb. of cement and 10·6 lb. of sand are used for a trial batch. To this a rather less quantity of water than will be actually used is added, say, in the proportion of 6 gallons per hundredweight of cement, or 2¼ pints for 5·3 lb. of cement, and the flow time through the cone is measured. More water, say ¼ pt., is then added and the flow time again determined. Further quantities of water are added and the test repeated until the grout shows signs of segregation or until the flow time becomes constant. Flow curves can then be drawn similar to those shown in *Fig.* 99, and the gallons of water required per hundredweight of cement for the required flow time read from the curve. If surface-dry sand is used in the test the amount of water contained in the sand as delivered for the work must be deducted from the quantity given on the curve.

Since the amount of water in the sand will vary in each delivery, the fluidity of the grout should be constantly checked by the flow cone.

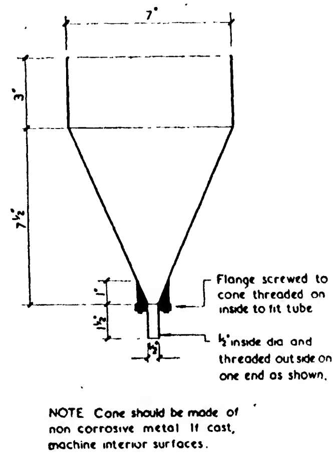


Fig. 98.—Apparatus for Measuring the Fluidity of Grout.

Fig. 99 also gives curves of flow times for three usual sand gradings and fluidities for proper penetration. Other sands with the same gradings but with different shaped grains may require widely different water contents for satis-

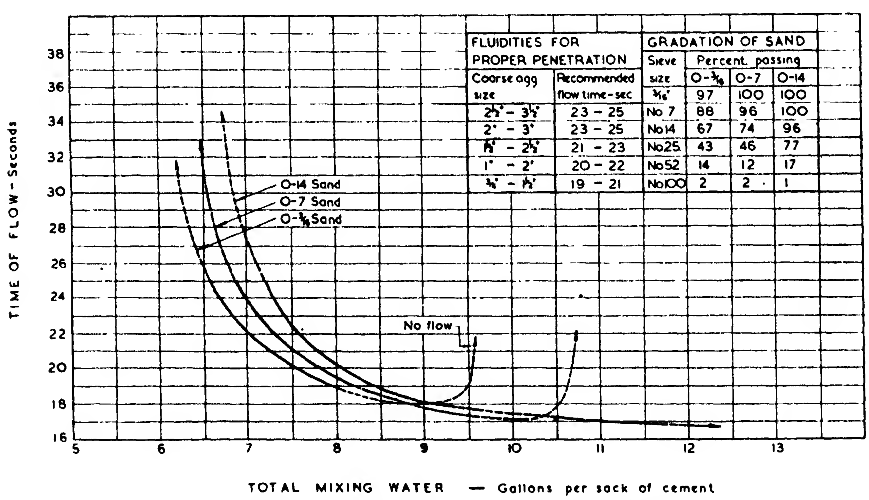


Fig. 99.—Determination of Quantity of Water Required for Grout.

factory fluidity; in such cases the proportion of cement should be increased to maintain the strength of the mortar. These curves show, as does the curve for any particular work, (1) The working limits of mix for the sand used, along the mid-portion of the curve where it is changing from vertical to horizontal, and

(2) the effect on flow time of changes in water content. *Table* XIX gives approximate quantities of materials for estimating purposes. In the table the quantities of fine aggregate and cement are based on the use of 7½ Imperial gallons of water per 112 lb. of cement and 224 lb. of dry sand, yielding 3·12 cu. ft. of grout. For other quantities of mixing water the yield would be increased or decreased by 0·16 cu. ft. for each gallon of mixing water above or below 7½. The quantities of sand and cement produce 17 per cent. of excess grout to allow for shrinkage due to loss of water by evaporation, and absorption by the aggregates and the sub-base, and waste. Figures for the settlement of the sub-base are for average

TABLE XIX.—QUANTITIES OF MATERIALS REQUIRED FOR CEMENT-GROUTED ROADS.

	Method of consolidation			Quantity of materials per cubic yard of completed road		
	Initial	Final	Settlement of sub-base (in.)	Coarse aggregate. Cu. yd. (loose volume)	Fine aggregate. Tons (dry)	Cement (lb.)
Crushed stone	Rolling	Rolling	¾	1·14	0·398	448
1 in–2 in. or	None	Rolling	1	1·05	0·446	504
1½ in–2½ in.	None	Hand	nil	1·02	0·462	518
47 per cent. voids	None	Vibration	nil	1·05	0·446	504
Crushed slag	Rolling	Rolling	¾	1·14	0·377	424
1 in.–2 in. or	None	Rolling	1	1·08	0·408	458
1½ in.–2½ in.	None	Hand	nil	1·02	0·441	496
45 per cent. voids	None	Vibration	nil	1·10	0·397	448
Gravel						
¾ in.–2 in. or	None	Rolling	¼	1·06	0·398	448
1½ in.–2½ in.	None	Hand	nil	1·04	0·412	462
43 per cent. voids	None	Vibration	nil	1·05	0·405	454

compacted soils. For clay soils 25 per cent. should be added. No allowance need be made for old compacted gravel and macadam sub-bases.

Construction.

FOUNDATION.—The foundation should be firm and even to give uniform support to the paving. Sand and other soft material should be compacted or removed; if left loose they will work up into the aggregate and prevent full penetration of the grout. Rolling the aggregate pushes an appreciable amount into very soft foundations, resulting in loss of stone and variation in thickness of the paving; this may be prevented by rolling a layer of coarse material, such as gravel, clinker, etc., into the foundation. Hand compaction is best on sandy foundations. Coarse aggregate should not be rolled on a foundation softened by rain.

COMPACTING THE STONE.—Compacting the coarse aggregate before grouting reduces the voids and therefore the quantity of grout required. The stone is keyed together and stabilized by the grout before the foundation is wet, making it easier to maintain a true surface under final compaction and reducing loss of stone in the foundation. Rolling with a tandem roller or hand tamping with long and heavy straightedges are common methods. A 3-ton to 6-ton tandem roller is most effective; with lighter rollers the loss of stone in the foundation is about the same but more grout is required because of less compaction. The roller should work parallel to the centre line, beginning at the edge or kerbs and working towards the centre with each track overlapping the preceding one by about one-half. Two rollings are generally sufficient. Hand tamping and vibration do not compact coarse stone very much and may be omitted prior to grouting. They do level the surface, however, and aid in securing smooth riding surfaces. Loss of stone in the foundation is negligible with both methods. Uncrushed round gravel cannot be rolled before it is grouted, but is easily rolled after grouting. Slag requires less rolling before grouting than crushed stone. Excessive rolling should be avoided as it may interfere with proper penetration of the grout.

Mixing the Grout.—For grout mixed on the site the sand, cement, and water should be mixed in a machine of the tilting-drum or closed-drum type for at least one minute after all ingredients, including water, have been placed in the drum. Small quantities may be mixed in a water tank or other suitable container, the cement and water being thoroughly mixed first and the sand added; this method requires constant agitation of the grout while the tank is being emptied, which may be by gravity through a 3-in. pipe or by buckets.

Grouting.—The grout should be deposited on the stone at the edge of the area already grouted to avoid trapping air and free water in the voids, and should proceed evenly from edge to edge of the paving while men with brooms direct the flow and work excess grout forward. The penetration of the grout should be checked at intervals by removing the stones down to the foundation a foot or two ahead of the grouted surface. Good penetration is obtained if unsegregated grout flows into the bottom of the hole.

Final Compaction.—Final compaction may be undertaken by (*a*) rolling, (*b*) vibration, or (*c*) hand-tamping.

Compaction by rolling should be done with a tandem roller weighing not less than three or more than six tons, starting when free water is no longer released from the grout to the surface and before there is undue hardening of the grout. The time between grouting and final rolling will range from 30 minutes to about one hour depending upon the temperature and other factors. The period between grouting and final compaction will be longer when the aggregate is not compacted before grouting. In some circumstances, such as high humidities, low temperatures, wet foundations, and other factors retarding the release and evaporation of water from the mass, it may be necessary to delay final rolling for as long as three or four hours after grouting.

If vibratory methods are used a tamper board should be used having a length slightly greater than the width of the paving upon which are mounted two or more vibrating units. The entire surface should be vibrated at least twice, or as often as is necessary to produce a dense even surface. During vibration light brooms should be used to distribute the grout evenly and to remove excess grout from the surface. Grout should be added to the surface where necessary to embed the stone properly. For the first passage the vibratory tamper should operate at a speed of about 5 ft. per minute, increasing to 7 ft. per minute for the second and any succeeding passages.

Where hand methods are used a tamping template weighing from 10 lb. to 15 lb. per foot and 12 ft. in length, with suitable handles and having a tamping face 4 in. to 5 in. wide, should be used. Immediately after grouting, the surface should be tamped once or twice to embed stones displaced during grouting, and tamping should proceed from kerb to kerb parallel with the centre line of the road. The tamper should be lifted vertically from 6 in. to 10 in. and allowed to fall, then moved transversely about the width of the tamping face for the next stroke. Tamping should proceed in this manner for the entire width of the pavement. Further compaction after an interval of time should be undertaken as described below.

FINISHING.—After compaction, surface irregularities of more than ¼ in., measured with a 10-foot straightedge, should be corrected either by the use of a hand tamper weighing not less than 25 lb. or by trimming such places with stone rakes and then re-compacting with the longitudinal tamping template. Hollow places should be filled with ⅜-in. to ½-in. stone and lightly tamped and brushed. If final compaction is by hand a period determined by weather and other conditions (usually about 30 minutes to one hour after grouting) should elapse between final compaction and finishing.

Curing should be carried out in the ordinary way as soon as it is possible to do so without damaging the surface.

Grouting Systems.

The grout may be made by a process which prepares the grout in a special mixer or by a process which requires the use of an admixture.

The "Colcrete" mixer consists of a twin-tank machine driven by a 10-h.p. petrol engine. In one tank the cement and water are combined to form a colloidal grout, which then passes into the second tank containing the sand. This mixer delivers grout with a head of 30 ft.; this is equivalent to a 60-ft. head of water, since the specific gravity of the grout is approximately two, and this pressure permits delivery to a distance of 150 ft. through a 2½-in. hose. The output under normal conditions is 60 mixes per hour, each mix requiring 1 cwt. of cement and 140 lb. of sand with about 7 gal. of water including moisture in the sand; this produces 2·55 cu. ft. of 1 : 1¼ grout. This represents 153 cu. ft. of grout per hour which, with stone containing 40 per cent. voids, is sufficient for a little more than 14 cu. yd. of finished work per hour. The labour requirement of this machine is: 1 man in charge of the mixer, 2 men on cement, 1 man on water, 2 men on sand, 1 man on the delivery hose, 2 men tamping and finishing, and 2 to 4 men spreading the stone, fixing forms, etc. This process may be applied to any suitable stone not less than 1 in. in size. Weak material, such as chalk, sandstone, hard-core, broken brick, etc., may be used as a bottom course followed by about 1½ in. of hard stone before grouting.

The "Cheecol" process consists in adding to the mixing water a chemical in liquid form at the rate of one gallon to two tons of cement or 4 fluid ounces per 112 lb. bag. Sand and cement, usually in the proportions of 1 cwt. of cement to 2 cu. ft. of sand (damp), are mixed in an ordinary mixer of the tilting-drum or closed-drum type. The mixing water, to which the required proportion of the liquid has been previously added, is drawn from the tank in the usual manner. For normal grout a water-cement ratio of 0·70 is satisfactory; this is equivalent to approximately 7¾ gal. per bag of cement, including moisture in the sand and the admixture. The grout may be applied by means of a chute or by discharging it into a container from which it is delivered by pump. The labour required is the same as for the process described in the preceding paragraph.

Rolled Concrete.

In this category are included cement-bound macadam roads and compressed (or rolled) concrete roads. In the former construction two separate layers of broken stone with an intermediate layer of sand-cement mortar are incorporated into one mass by rolling. Compressed or rolled concrete consists of sand, cement and stone mixed in a machine with a small amount of water and rolled to the required density and shape. Both types require a sound foundation, such as an existing road bed or road surface. Should the old road be potholed it may be scarified and rolled or the potholes may be filled with coarse material well rolled to form a foundation of uniform load-bearing capacity.

Cement-Bound Macadam.—The first road of this type constructed in this country was laid by the Hoo (Kent) Rural District Council in 1926, and this was followed by experimental sections in other districts. The proportions of the mortar, the size of stone, and details of construction have been gradually standardised. The advantages of the cement-bound macadam road are that it provides (*a*) a non-slippery surface which, by brushing, can be made sufficiently rough to suit any gradient on which a road roller can operate; (*b*) an excellent foothold for horses; and (*c*) a surface similar in appearance to that of waterbound macadam.

The operations required in the construction of cement-bound macadam paving may be described briefly as follows:

(1) Spreading broken stone—approximately 2-in. B.S. gauge—in a layer 2 in. thick and lightly rolling;

(2) Spreading mortar in the proportions of 1 part of cement to 2 parts of damp sand by volume about 1 in. thick on the bottom layer of stones.

(3) Spreading a top layer of stone of the same gauge and depth as the bottom layer.

(4) Rolling, working from the kerbs to the centre, until the mortar sandwich works up to the surface. A satisfactory roller for this work is a 7-8 ton tandem.

(5) On completion of rolling, irregularities, wheel marks, etc., are removed by a light roller or by hand tamping. The surface is then given a light brushing just sufficient to expose the coarse aggregate.

(6) About half-an-hour after completion any raw places or voids are filled with grout of the same proportions as the mortar sandwich.

The stone should be granite, basalt, hard limestone, or similar material, cubical in shape and free from flour or dust. The sand for the mortar should be clean and graded from $\frac{3}{16}$ in. down.

An area of 100 sq. yd. 3½ in. to 4 in. thick requires 1⅞ tons of cement, 4½ tons (approximately 5½ cu. yd.) of damp sand, and 15 tons of stone. The labour required comprises: 1 roller driver, 1 mixer driver, 2 men loading the mixer, 2 men barrowing the mortar, 4 men spreading stones and mortar, fixing forms, etc., and 2 men brushing and finishing the surface.

Compressed Concrete.—This construction was first developed in Ireland in order to utilize small-gauge stone not suitable for cement-bound macadam work. Cement, sand, and stone in the approximate proportions of 1 : 2 : 6 are mixed together in an ordinary mixer, spread to the required thickness, and consolidated by a roller not less than 5 tons in weight. The main requirements for successful work are the use of correct proportions of stone and sand and a water content sufficiently low to permit compaction by rolling. Water-cement ratios not higher than 0·40 by weight are generally satisfactory ; it is advisable, however, first to adjust the stone-sand ratio and to lay one or two small trial lengths before proceeding with the main work. One of the chief advantages of this construction is that rubber-tyred traffic can pass over the surface immediately after completion, and for this reason it is very suitable for surfacing roads in rural areas which cannot be closed to traffic. If full advantage is to be taken of this construction it is necessary for comparatively large quantities of concrete to be quickly available, as the roller can compact and finish the concrete almost as fast as it can be spread.

The quantities of cement, sand, and stone per cubic yard (say, 9 sq. yd. 4 in. thick) will be those required for a nominal 1 : 2 : 6 mix, namely, 405 lb. of cement, 0·34 cu. yd. of sand, and 1 cu. yd. of stone.

FIG. 99(*a*).—WOOD CURING FRAME COVERED WITH TARPAULIN OR WATERPROOF PAPER.

FIG. 99(*b*).—WOOD CURING FRAME UNDER WHICH A LAYER OF STRAW CAN BE PLACED.

CHAPTER XVI

CURING

If the water dries out before the cement has reached a large part of its ultimate strength, the strength and wearing properties of concrete are reduced. The curing periods recommended are 5 and 7 days respectively in the case of rapid-hardening Portland cement and ordinary Portland cement when the temperature is about 60 deg. Fahr.; at temperatures of about 40 deg. these periods should be doubled. Coloured concrete should be cured for 7 days in summer and 10 days in winter when rapid-hardening Portland cement is used, and twice as long with ordinary Portland cement. One day's curing is sufficient at any temperature when high-alumina cement is used. At some times of the year there may be no need for curing, but it is customary to specify periods during which the concrete must not be allowed to dry out or be subject to freezing.

Apart from the use of a hose, which is not recommended because the concrete may be allowed to dry out between the applications of water, at normal temperatures the cheapest method is to cover the concrete with 2 in. or 3 in. of damp soil or sand as soon as possible without damaging the surface. If the shade temperature is 60 deg. Fahr. or higher the surface should be covered with waterproof paper, tarpaulin, or damp hessian weighing not less than 7 oz. per sq. yd., immediately the concrete is placed, and later replaced with sand or earth which should be kept wet for the periods stated. The paper or similar covering should extend 18 in. beyond the edges of the slab and the overlaps should be 6 in. In very hot weather ridges of clay may be placed along the sides of a fairly level road, and transversely at about 15-ft. intervals, and 2-in. or so of water maintained in the shallow ponds so formed.

Coloured concrete is best kept covered with tarpaulins or waterproof paper during the whole of the curing period, as the application of water has been known to cause efflorescence.

In normal winter weather the frames shown in *Figs.* 99(*a*) and 99(*b*) are suitable. These can be removed to water the concrete, and replaced. In exceptionally severe conditions more expensive protection is necessary, such as a higher cover under which braziers may be kept burning.

If the temperature of the concrete is raised to 60 deg. Fahr. when it is placed and it is immediately covered with 1 ft. of hay or straw and a covered frame, it has been found to harden satisfactorily at air temperatures as low as 9 deg. below zero. The temperature of the concrete can be raised by heating the mixing water to about 160 deg. Fahr. and prolonging the mixing for ten minutes.

The addition of 2 per cent. of calcium chloride by weight of cement will cause the cement to have an initial set of about 40 minutes and a final set of about 2 hours, thus reducing the period during which frost can seriously affect it. The salt should not be used if the road is reinforced due to risk of corrosion of the steel. Calcium chloride is sometimes used for curing. The practice is to keep the surface of the concrete wet for not less than 12 hours and while it is wet sprinkle on calcium chloride at the rate of 1½ lb. per sq. yd. and spread it uniformly with a squeegee or by other means.

The retention of mixing water by sealing the surface has been practised in recent years. The United States Bureau of Reclamation uses an emulsion comprising: Paraffin, 49·7 lb.; boiled linseed oil, 74·5 lb.; triethanolamine, 13·2 lb.; stearic acid, 16·6 lb.; soft water, 248·3 lb. All the ingredients except the triethanolamine are heated together and stirred until the solids are dissolved. The triethanolamine is then added and stirring continued until the mixture is cool. About 18 r.p.m. is a suitable rate of stirring. The solution is applied at the rate of 1 gall. to 150 sq. ft. immediately the slab is finished, or the surface kept moist until the emulsion is applied with paint-spraying equipment, using a pressure pot with an agitator.

If the formation is dry it should be well watered before concrete is placed, or concreting paper placed over it, to prevent the escape of mixing water to the formation. The formation should be covered with waterproof paper if it contains, or is suspected to contain, sulphates or other chemicals that would injure the concrete.

APPENDIX I

QUANTITIES OF MATERIALS REQUIRED PER CUBIC YARD OF CONCRETE

THE following table gives the approximate quantities of materials required per cubic yard of concrete when either gravel or broken stone is used as the coarse aggregate, and for sand that is either dry or which has bulked 20 per cent. on account of its moisture content. The cement quantities are based on ordinary Portland cement weighing 90 lb. per cubic foot. Since the exact quantities required to make one cubic yard of hardened concrete depend on such factors as the water content of the mix, its degree of compaction, the type of coarse and fine aggregate and the voids therein, the quantities are, of course, only approximate.

Nominal mix (dry material)	Approx. water-cement ratio by weight	Bulking of sand	GRAVEL (40 per cent. Voids) Nil Proportions	GRAVEL Nil Quantities per cubic yard	GRAVEL 20 per cent. Proportions	GRAVEL 20 per cent. Quantities per cubic yard	BROKEN STONE (45 per cent. Voids) Nil Proportions	BROKEN STONE Nil Quantities per cubic yard	BROKEN STONE 20 per cent. Proportions	BROKEN STONE 20 per cent. Quantities per cubic yard
1 : 1 : 2	0·35	Cement (lb.)	112	914	112	914	112	950	112	950
		Sand (cu. ft.)	1·25	9·7	1·50	11·6	1·25	10·26	1·50	12·3
		Stone (cu. ft.)	2·50	19·4	2·50	19·4	2·50	20·50	2·50	20·5
1 : 1½ : 2	0·40	Cement (lb.)	112	809	112	809	112	839	112	839
		Sand (cu. ft.)	1·87	12·7	2·24	15·2	1·87	13·20	2·24	15·8
		Stone (cu. ft.)	2·50	17·3	2·50	17·3	2·50	17·80	2·50	17·8
1 : 1½ : 3	0·45	Cement (lb.)	112	671	112	671	112	700	112	700
		Sand (cu. ft.)	1·87	10·5	2·24	12·6	1·87	11·00	2·24	13·2
		Stone (cu. ft.)	3·75	21·0	3·75	21·0	3·75	22·00	3·75	22·0
1 : 2 : 3	0·50	Cement (lb.)	112	612	112	612	112	638	112	638
		Sand (cu. ft.)	2·50	13·0	3·00	15·6	2·50	13·50	3·00	16·2
		Stone (cu. ft.)	3·75	19·4	3·75	19·4	3·75	20·20	3·75	20·2
1 : 2 : 4	0·55	Cement (lb.)	112	529	112	529	112	556	112	556
		Sand (cu. ft.)	2·50	11·3	3·00	13·5	2·50	11·80	3·00	14·1
		Stone (cu. ft.)	5·00	22·6	5·00	22·6	5·00	23·60	5·00	23·6
1 : 2½ : 4	0·60	Cement (lb.)	112	493	112	493	112	513	112	513
		Sand (cu. ft.)	3·12	13·0	3·74	15·6	3·12	13·50	3·74	16·2
		Stone (cu. ft.)	5·00	21·0	5·00	21·0	5·00	21·80	5·00	21·8
1 : 2½ : 5	0·65	Cement (lb.)	112	437	112	437	112	457	112	457
		Sand (cu. ft.)	3·12	11·6	3·74	13·9	3·12	12·00	3·74	14·4
		Stone (cu. ft.)	6·25	23·2	6·25	23·2	6·25	24·00	6·25	24·0
1 : 3 : 5	0·70	Cement (lb.)	112	411	112	411	112	431	112	431
		Sand (cu. ft.)	3·75	13·0	4·50	15·6	3·75	13·70	4·50	16·5
		Stone (cu. ft.)	6·25	21·8	6·25	21·8	6·25	23·00	6·25	23·0
1 : 3 : 6	0·75	Cement (lb.)	112	371	112	371	112	391	112	391
		Sand (cu. ft.)	3·75	11·8	4·50	14·1	3·75	12·40	4·50	14·9
		Stone (cu. ft.)	7·50	23·6	7·50	23·6	7·50	24·80	7·50	24·8
1 : 4 : 8	0·80	Cement (lb.)	112	286	112	286	112	302	112	302
		Sand (cu. ft.)	5·00	12·0	6·00	14·4	5·00	13·00	6·00	15·6
		Stone (cu. ft.)	10·00	24·0	10·00	24·0	10·00	26·00	10·00	26·0

APPENDIX II

TESTING CONCRETE AND CONCRETE MATERIALS

IN this Appendix are given some of the standard methods recommended for sampling and testing aggregates and concrete for use in roads and other concrete work.

Size of Sample of Aggregate.

According to British Standard No. 882—1944, a main representative sample of aggregate of ½ cu. yd. (or 12 cwt.) shall be taken and reduced by quartering to the following quantities for use in the tests stated. Sieve analysis: 2½ in. and 1½-in. aggregate, 50 lb.; ¾-in. aggregate, 20 lb.; ½-in. aggregate, 10 lb.; ⅜-in. aggregate, 5 lb.; fine aggregate, 1 lb. Specific gravity and water absorption: 2 lb. Bulk density: 2½-in. aggregate, 150 lb.; 1½-in., ¾-in., ½-in., and ⅜-in. aggregate, 75 lb.; fine aggregate, 15 lb. Organic impurity: 1 lb.

Sieve Analysis.

The Code of Practice standard method of sieve analysis of aggregates is as follows. The sample, obtained by quartering, shall weigh not less than: Fine aggregate, 3 lb.; coarse aggregate, 10 lb.; where fine and coarse aggregates are to be used combined, 15 lb. (It will be noted that these samples are smaller than those required by the British Standard test.) The sample shall be dried to constant weight at a temperature not exceeding 230 deg. F. Unless otherwise stated the sample shall be separated by means of the following B.S. sieves, 1½-in., ¾-in., ⅜-in., $\frac{3}{16}$-in., Nos. 7, 14, 25, 52 and 100. Sieving shall be continued until not more than 1 per cent. by weight of the residue passes any sieve during one minute. Each size shall be weighed on a scale which is sensitive to 0·001 of the weight of the sample. The percentage by weight of the total sample which is finer than each of the sieves shall be computed.

Shape of Aggregates.

B.S. No. 882 describes various shapes of particles of coarse aggregate as follows. Rounded (*Fig.* 100): Fully waterworn or completely shaped by attrition, such as river and beach gravels and beach and wind-blown sands. Irregular (*Fig.* 101): Naturally irregular, or partly shaped by attrition, and having rounded edges, such as pit sands and gravels, flints, and cuboid rock. Angular (*Fig.* 102): Possessing well-defined edges formed at the intersection of roughly plane faces, including crushed rocks of all types, talus, and screes. Flaky (*Fig.* 103): Material, usually angular, of which the thickness is small relative to the width or length, or to both, such as laminated rocks.

Sedimentation Test for Clay, Silt, and Dust.

A sample of the aggregate is filled up to the 100-ml. mark of a 200-ml. standard test cylinder, and water added up to the 150-ml. mark. The cylinder is then vigorously shaken, and its contents allowed to settle for three hours. The silt will then be visible above the sand, and the material is suitable for concrete making if the silt does not exceed 6 per cent. by volume or 6 per cent. by weight of the sample. A more exact laboratory method is given in B.S. No. 882.

Determination of Organic Impurities.

The British Standard approximate method of estimating the amount of organic compounds present in sand is as follows. A 12-oz. medicine bottle is filled with sand to the 4½-oz. mark, and a 3 per cent. solution of sodium hydroxide in water is added until the total volume, after shaking, is 7 oz. The bottle is then stoppered, shaken vigorously, and allowed to stand for 24 hours. The amount of organic impurity present is indicated by the colour of the solution above the sand, and the sand should not be used if this colour is darker than the standard solution. The standard solution is made by adding 2·5 ml. of a 2 per cent. solution of tannic acid in 10 per cent. alcohol to 97·5 ml. of a 3 per cent. sodium hydroxide solution. This is placed in a bottle, stoppered, shaken vigorously, and allowed to stand for 24 hours before being used for

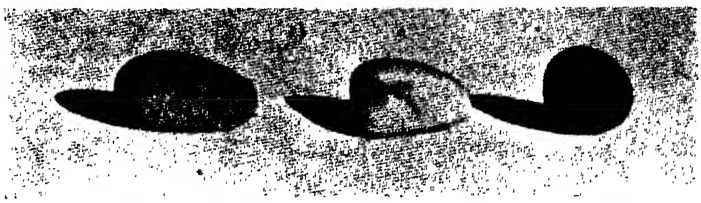


FIG. 100.—ROUNDED AGGREGATE.

FIG. 101.—IRREGULAR AGGREGATE.

FIG. 102.—ANGULAR AGGREGATE.

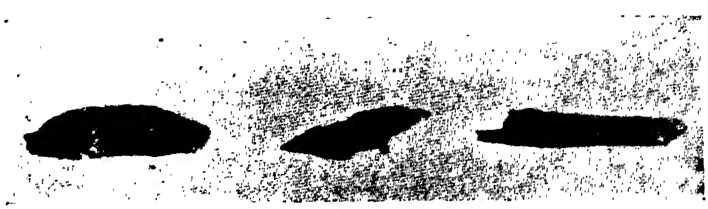


FIG. 103.—FLAKY AGGREGATE.

the purpose of comparison. Alternatively, the colour may be compared with a piece of glass known as " deep amber polished plate," obtainable from Messrs. Pilkington Bros., Ltd., of St. Helens, which is the same colour as the standard solution. If the test shows that the sand is of doubtful quality it is best to compare the strength of concrete made with the sand in question and with sand of known quality.

Bulk Density, or Unit Weight, of Aggregates.

B.S. No. 882 recommends the following method of ascertaining the bulk density or unit weight of a material, that is the weight of the material held by a container of unit volume when filled or compacted under defined conditions.

A cylindrical metal measure, a tamping rod, and a balance sensitive to 0·5 per cent. of the weight of the sample are required. The measure is preferably provided with handles; it should also be watertight and of sufficient rigidity to retain its form under rough usage. The measure must comply with the requirements of the following table.

Size of largest particles	Nominal capacity	Inside diameter	Inside height	Minimum thickness of metal
	cu. ft.	in.	in.	S.W.G.
Under $\frac{3}{16}$ in.	$\frac{1}{10}$	6	6·10	11
From $\frac{3}{16}$ in. to $1\frac{1}{2}$ in. . . .	$\frac{1}{2}$	10	11·00	8
Over $1\frac{1}{2}$ in.	1	14	11 23	5

The measure is calibrated by determining the weight of water at 20 deg. C. required to fill it so that no meniscus is present above the rim of the container. The capacity in cubic feet is then obtained by dividing the weight in pounds of water required to fill the container at 20 deg. C. by the weight of water in 1 cu. ft. (62·4 lb.) at 20 deg. C. The tamping rod is a straight metal rod $\frac{5}{8}$ in. in diameter and 2 ft. long, round-nosed at the lower end.

Rodded or Compacted Weight.—The measure is filled about one-third full with the aggregate (previously dried and thoroughly mixed) and tamped with 25 strokes of the rod. A further similar quantity is then added and a further tamping of 25 strokes given. The measure is finally filled to overflowing, tamped 25 times, and the surplus struck off.

Loose Weight.—The measure is filled to overflowing, the aggregate being discharged from a height not exceeding 2 in. above the top of the measure. Care must be taken to prevent separation of the particle sizes. The surface is then levelled with a straightedge.

The net weight of aggregate in the measure is determined and the bulk density calculated in lb. per cubic foot. The condition of the aggregate at the time of test must be stated, i.e. oven dry, saturated and surface dry, or with a given percentage of moisture.

Determination of Voids.

The following method is recommended in B.S. No. 882. It is suitable for fine or coarse aggregates tested separately, but it cannot be used for all-in material owing to the marked segregation occurring when all-in aggregate is inundated, or for aggregates of high porosity. The apparatus required is the same as is used for the determination of bulk density.

The measure (volume A) is filled about one-third full with a measured volume of water. Sufficient dry aggregate is then added to fill the measure to a depth of about one-third, and this layer is given 25 strokes with the tamping rod. A further similar quantity of aggregate is added and a further 25 strokes with the tamping rod given. The measure is then filled to overflowing, tamped 25 times, and the surplus aggregate struck off. Further water is then added from a measuring cylinder until the measure is exactly filled. The total volume of water used is recorded as volume B. It sometimes occurs with materials of comparatively low voids content, that water overflows from the measure when the last layer of aggregate is added. The volume of water thus expelled must be determined, and this will be facilitated if the measure is allowed to stand on a flat-bottomed dish during filling.

The approximate voids are expressed as a percentage by means of the formula

$$\text{Percentage voids} = \frac{B}{A} \times 100.$$

The proportion of voids can also be calculated by

$$\text{Percentage of voids} = \frac{G^1 \times 62{\cdot}4 - BD}{G^1 \times 62{\cdot}4} \times 100$$

where G^1 = gross " apparent " specific gravity on a dry basis as defined in the following (the apparatus required and the method of determining gross " apparent " specific gravity are given in B.S. No. 882), and BD = bulk density as determined in the test for bulk density already described.

Specific Gravity.

The following definitions of specific gravity are from B.S. No. 882.

" Apparent " specific gravity.—The apparent specific gravity of a material is the ratio of the weight in air of a certain volume of the solid, including in the volume such proportion of the pores as the test conditions define, to the weight of an equal volume of water at the same temperature.

Gross " apparent " specific gravity.—The gross " apparent " specific gravity of a material is the ratio of the weight in air of the total volume of the solid including all pores in this total volume, to the weight of an equal volume of water at the same temperature. It may be expressed on a dry or on a saturated and surface dry basis.

Absolute specific gravity.—The absolute specific gravity of a material is the ratio of the weight in vacuum of a certain volume of the material (excluding the volume of all pores) to the weight also in vacuum of the same volume of water.

Consistency of Concrete.

The slump test for measuring the consistency of concrete is described as follows in the Code of Practice and in B.S. No. 882.

The test specimen shall be formed in a mould in the form of the frustrum of a cone with internal dimensions as follows : Bottom diameter, 8 in. ; top diameter, 4 in. ; height, 12 in. The bottom and the top shall be open, parallel to each other, and at right angles to the axis of the cone. The mould shall be provided with foot pieces and handles. The internal surface shall be smooth. The internal surface of the mould shall be thoroughly clean, dry, and free from set cement. The mould shall be placed on a smooth, flat, non-absorbent surface, and the operator shall hold the mould firmly in place, while it is being filled, by standing on the foot pieces. Care shall be taken to ensure that a representative sample is taken. The mould shall be filled to about one-fourth of its height with the concrete, which shall then be puddled, using 25 strokes of a $\frac{5}{8}$-in. rod, 2 ft. long, bullet pointed at the lower end. The filling shall be completed in successive layers similar to the first and the top struck off so that the mould is exactly filled. The mould shall then be removed by raising vertically, immediately after filling. The moulded concrete shall then be allowed to subside and the height of the specimen measured after coming to rest. The consistency shall be recorded in terms of inches of subsidence of the specimen during the test, which shall be known as the slump.

Works Cube Tests of Concrete.

The method described is that recommended in the Code of Practice and applies to compression tests of concrete sampled during the progress of the work.

Size of Test Cubes and Moulds.—The test specimens shall be 6-in. cubes. The moulds shall be of steel or cast iron, with inner faces accurately machined in order that opposite sides of the specimen shall be plane and parallel. Each mould shall be provided with a base plate having a plane surface and of such dimensions as to support the mould during filling without leakage and preferably attached by springs or screws to the mould. Before placing the concrete in the mould both the base plate and the mould shall be oiled to prevent sticking of the concrete.

Sampling of Concrete.—Wherever practicable concrete for the test cubes shall be taken immediately after it has been deposited in the work. Where this is impracticable samples shall be taken as the concrete is being delivered at the point of deposit, care being taken to obtain a representative sample. All the concrete for each sample shall be taken from one place. A sufficient number of samples, each large enough to make one test cube, shall be taken at different points so that the test cubes made from them will be representative of the concrete placed in that portion of the structure selected for tests. The location from which each sample is taken shall be noted clearly for future reference. In securing samples the concrete shall be taken from the mass by a shovel or similar implement and placed in a large pail or other receptacle, for transporting to the place of moulding. Care shall be taken to see that each test cube represents the total mixture of concrete from a given place. Different samples shall not be mixed together but each sample shall make one cube. The receptacle containing the concrete shall be taken to the place where the cube is to be moulded as quickly as possible and the concrete shall be slightly re-mixed before placing in the mould.

Consistency.—The consistency of each sample of concrete shall be measured, immediately after re-mixing, by the slump test. Provided that care is taken to ensure that no water is lost the material used for the slump tests may be re-mixed with the remainder of the mix before making the test cube.

Compacting.—Concrete test cubes shall be moulded by placing the fresh concrete in the mould in three layers, each layer being rammed with a steel bar 15 in. long and having a ramming face 1 in. square and a weight of 4 lb. For mixes of 1½-in. slump or less, 35 strokes of the bar shall be given for each layer; for mixes of wetter consistency the number may be reduced to 25 strokes per layer.

Curing.—The test cubes shall be stored at the site of construction, at a place free from vibration, under damp sacks for 24 hours (± ½ hour), after which time they shall be removed from their moulds, marked, and buried in damp sand until the time for sending to the testing laboratory. They shall then be well packed in damp sand or other suitable damp material and sent to the testing laboratory, where they shall be similarly stored until the date of test. Test cubes shall be kept on the site for as long as practicable but at least three-fourths of the period before test except for tests at ages less than seven days. The temperature of the place of storage on the site shall not be allowed to fall below 40 deg. F., nor shall the cubes themselves be artificially heated.

Record of Temperatures.—A record of the maximum and minimum day and night temperatures at the place of storage of the cubes shall be kept during the period the cubes remain on the site.

Method of Testing.—All compression tests on concrete cubes shall be made between smooth plane steel plates without end packing, the rate of loading being kept approximately at 2,000 lb. per square inch per minute. One compression plate of the machine shall be provided with a ball seating in the form of a portion of a sphere, the centre of which falls at the central point of the face of the plate. All cubes shall be placed in the machine in such a manner that the load shall be applied to the sides of the cubes as cast.

APPENDIX III

METHOD OF CLASSIFYING SOILS ACCORDING TO THEIR BEARING CAPACITIES

THE Public Roads Administration of the United States has devised a system for classifying soils according to their capacity to support wheel loads which depends upon the reactions of the soil to loading and climatic changes. These reactions depend upon the cohesion, internal friction, compressibility, elasticity, and capillarity of soils. Among the physical test constants which are used in identifying the important subgrade properties are the following: Plasticity (liquid limit, plastic limit, plasticity index); Volume change (shrinkage limit); Resistance to flow of water (centrifuge moisture equivalent); Moisture capacity of soils (field moisture equivalent). In addition, the grain size, as determined by mechanical analysis, is of importance. The chief value of the soil constants and grain size as a means of identifying subgrade soils lies in the relation between them rather than in the test results considered separately.

MECHANICAL ANALYSIS.—To determine the size and grading of the particles, the sizes retained on a No. 200 U.S. sieve are ascertained by sieve analyses. The sizes of the particles passing a No. 200 U.S. sieve are determined by hydrometer analyses based on Stokes's law that particles of equal specific gravity settle in water at a rate which is proportional to the size of the particle.

LIQUID LIMIT.—The liquid limit is defined as that moisture content, expressed as a percentage by weight of the oven-dry soil, at which the soil will just begin to

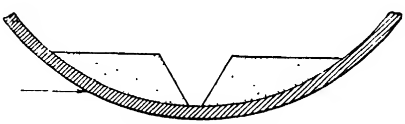


FIG. 104.—SOIL BEFORE TEST.

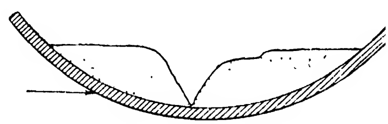


FIG. 105.—SOIL AFTER TEST.

flow when jarred slightly. The sample is placed in a dry porcelain evaporating dish about $4\frac{1}{2}$ in. diameter, shaped into a smooth layer approximately $\frac{3}{8}$-in. thick at the centre, and divided into two portions (*Fig.* 104) by means of a grooving tool of standard dimensions. The dish is held firmly in one hand and tapped lightly ten times against the palm of the other hand. If the lower edges of the two portions do not flow together, as shown in *Fig.* 105, the moisture content is below the liquid limit. If they flow together before ten blows the moisture content is above the liquid limit. The test is repeated with more or less moisture until the two edges meet exactly after ten blows. The arrows indicate the direction of the blows on the dish. A mechanical device is used in most American laboratories for the same test.

PLASTIC LIMIT.—The plastic limit is the moisture content expressed as a percentage by weight of the oven-dry soil at which cohesive soils pass from the semi-solid to the plastic state. The plastic limit, which is also the moisture content at which the coefficient of permeability of homogeneous clay becomes practically zero, is reached when the soil can be rolled into threads $\frac{1}{8}$ in. in diameter without breaking into pieces under pressure exerted by the hand. *Figs.* 106 and 107 show the nature of the test. The sample in *Fig.* 106 having a moisture content above the plastic limit, can be rolled into threads $\frac{1}{8}$ in. in diameter without crumbling. *Fig.* 107 shows a soil thread which has crumbled because the moisture content has been reduced by evaporation to the plastic limit or below.

PLASTICITY INDEX.—The plasticity index is the difference between the liquid limit and the plastic limit, and is the range of moisture content through which the soil is plastic.

Shrinkage Limit.—The shrinkage limit is the moisture content, expressed as a percentage by weight of oven-dry soil, at which a reduction in moisture content will not cause a decrease in volume of the soil but at which an increase in moisture content will cause an increase in volume of the soil.

Centrifuge Moisture Equivalent.—The centrifuge moisture equivalent is the moisture content, expressed as a percentage by weight of oven-dry soil, retained by a soil which has first been saturated with water and then subjected to a force equal to 1,000 times the force of gravity for one hour. The test consists of first soaking a small sample of air-dried soil with water in a Gooch crucible, draining it on a humidifier for at least twelve hours and then centrifuging it for one hour. The effect of the centrifugal force on the soil moisture is shown in *Fig.* 108.

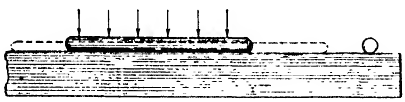


Fig. 106.—Soil above Plastic Limit.

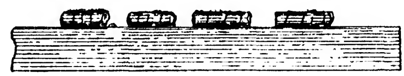


Fig. 107.—Soil below Plastic Limit.

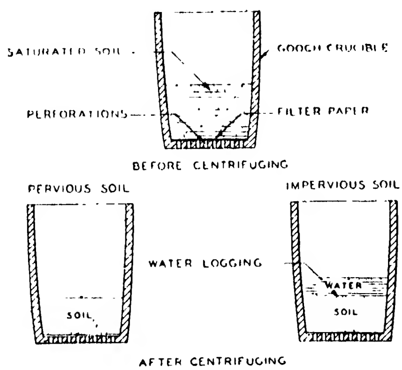


Fig. 108.—Centrifuge Test.

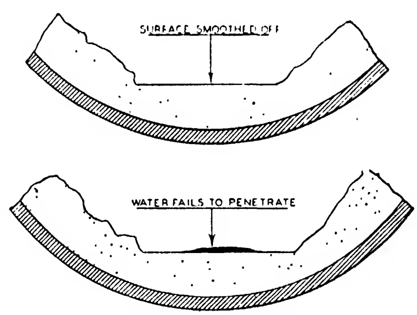


Fig. 109.—Moisture Equivalent Test.

Field Moisture Equivalent.—The moisture equivalent is the minimum moisture content, expressed as a percentage by weight of oven-dry soil, at which a drop of water placed on the smooth surface of the soil will not be immediately absorbed but will spread out over the surface and give it a shiny appearance (*Fig.* 109).

Soil Classification.

Based upon their field performances soils have been classified in groups designated A-1 to A-8 (see *Table* XX). This method of classification does not eliminate possible overlapping or provide a rigid measure of soil behaviour. Thus, some soils may have some of the characteristics of other groups. The engineer should judge the value that different soils may have, and the difficulties which may arise in their use, more upon the basis of their physical constants and their relationship than upon the fact that the soils fall in certain groups. This is illustrated by the fact that clay soils from different locations classed in groups A-6 or A-7 may have a wide range of plasticity and therefore may have different values for fill and foundation treatment. The soil classification should therefore be used to designate general characteristics such as permeability, bearing power, resistance to frost movement, etc.

Group A-1.—Soils of this group are composed of sandy material well graded from coarse to fine, mixed with a good binder. They are highly stable under wheel loads irrespective of moisture conditions and can be rolled to very high densities giving high bearing power. The soil mortar [that is, the fraction passing the No. 10 U.S. sieve (nearest B.S. sieve, No. 8)] should be graded as follows : Clay, 5 to 10 per cent. ; silt, 10 to 20 per cent. ; total sand, 70 to 85 per cent. ; coarse sand, 45 to 60 per cent.

Group A-2.—Soils of this group are composed of coarse and fine materials mixed with binder, but are inferior to A-1 soils due to poor grading, inferior binder, or both. A-2 soils can be compacted with either tamping or smooth-faced rollers, the density obtainable depending upon the amount, grading, and character of the binder. Portland cement and other admixtures can be mixed with soils of this group with comparative ease. The sand content is not less than 55 per cent.

Group A-3.—Soils of this group are composed entirely of coarse materials such as sand and gravel ; they lack stability under wheel loads except when damp ; they are only slightly affected by moisture conditions, and they have no volume change. They cannot be compacted by rolling, but in most cases may be settled by disking and ponding. They drain rapidly, and when adequately confined make suitable foundations for all types of road. The fraction passing the No. 200 sieve is less than 10 per cent.

Group A-4.—This group consists predominantly of silt soils containing moderate to small amounts of coarse material and small amounts of sticky colloidal clay. These soils vary widely in textural composition and range from sandy loams to silt and clay loams. They are subject to movement by frost. The silts and silt loams are relatively unstable at all moisture contents, but especially at the higher moisture contents when they have very low bearing capacity. The clay loams of this group are somewhat better graded than are the silts and can be rolled to higher densities. On heavy clay loams tamping rollers have proved more effective than rollers of the smooth-faced type. Clay loams are stable at the lower moisture contents and higher densities, but under these conditions are likely to show detrimental volume change if the moisture content is increased. The sand content is less than 55 per cent. These when wet may become elastic and show considerable rebound on removal of load. The more plastic types expand with increases in moisture in sufficient degree to cause warping at the joints in concrete slabs if the soils are placed at moisture contents lower than the optimum. Under a fixed set of test conditions each soil has a maximum weight per unit of volume at one moisture content, known as the optimum moisture content.

Group A-5.—This group is similar to group A-4 except that it includes very poorly graded soils which contain materials such as mica and diatones which are productive of elastic properties and very low stability. These soils are likely to be elastic and to rebound upon removal of load, even when dry. With a few exceptions the sand content is less than 55 per cent. These soils are subject to movement by frost action and are usually difficult to compact due to their tendency to rebound upon removal of load.

Group A-6.—This group is composed predominantly of clay soils with moderate to negligible amounts of coarse material. In the stiff or soft plastic state they absorb water only when manipulated. They can be compacted to relatively high densities by heavy rollers and can best be compacted with tamping rollers ; they have good bearing capacity when compacted to maximum practical density ; they are compressible and rebound very little upon removal of load. They are very expansive and, if placed sufficiently dry to allow water to be absorbed in large quantities, they may cause severe warping of superimposed concrete slabs. The sand content is less than 55 per cent. The high plasticity of these soils indicates the very cohesive nature of the binder (clay and colloids) at the lower moisture contents. The cohesion decreases as the moisture content increases, and as they possess little internal friction these soils are only suitable when they can be placed and maintained at a relatively low moisture content. This group is characterised by shrinkage cracks on all surfaces exposed to drying. Soils of group A-6 are confined within closer limits on their general characteristics than those of groups A-4 or A-7. When concrete slabs are placed over these soils the sub-base should be covered with non-expansive materials or compacted to high densities with carefully-controlled moisture contents.

Group A-7.—Soils of this group are similar to those of group A-6 except that at certain moisture contents they deform quickly under load and recover appreciably

TABLE XX.

GROUP	A-1	A-2 Friable	A-2 Plastic	A-3	A-4	A-5	A-6	A-7	A-8
General characteristics	Predominantly sandy soil well-graded; coarse to fine; exc. binder.	Sandy soil. Poor grading. Poor binder.	Sand and gravel. Poor grading. Inferior binder.	Sand and gravel. Coarse material only; no binder.	Silt soil with fine sand and friable clay. Compressible.	Silt soil with micaceous and diatomaceous material. Elastic.	Clay soils. Deflocculated cohesionless clays. Compressible.	Clay soils. Drainable flocculated clays. Elastic.	Peat and dirt.
Physical characteristics									
Liquid limit	14-35	35 max.	35 max.	Non-plastic	20-40	35 min.	35 min.	35 min.	35-400
Plasticity index	4-9	Non-plastic-3	3-15	" "	0-15	0-60	18 min.	12 min.	0-60
Field moisture equivalent	Not essential	Not essential	Not essential	Not essential	30 max.	30-120	50 max.	30-100	30-400
Centrifuge moisture equivalent	15 max.	12-25	25 max.	12 max.	Not essential	Not essential	Not essential	Not essential	Not essential
Shrinkage limit	14-20	15-25	25 max.	Not essential	20-30	30-120	6-14	10-30	30-120
Volume change	0-10	0-6	0-16	Nil	0-16	0-16	17 min.	17 min.	4-200
Lineal shrinkage	0-3	0-2	0-4	Nil	0-4	0-4	5 min.	5 min.	1-30
General stability properties	High stable at all times	Stable when dry, may ravel	Good stable material	Ideal support when confined	Satisfactory when dry, loss of stability when wet	Difficult to compact; stability doubtful.	Good stability when well compacted	Good stability when well compacted	Incapable of support
Max. dry weight lb./cu.ft.	130 min.	120-130	120-130	120-130	110-120	80-100	80-110	80-110	90 max.
Optimum moisture percentage of dry weight (approx.)	9	9-12	9-12	9-12	12-17	22-30	17-28	17-28	-
Required total thickness for sub-base, base and surfacing - inches	0-6	0-6	2-8	0-6	9-18	9-24	12-24	12-24	-

upon removal of load. Alternate wetting and drying leads to rapid and detrimental volume changes ; they have good bearing capacities when compacted to high densities. These soils have produced more severe warping of concrete slabs than have soils of other groups. The sand content is less than 55 per cent. The major difference between soils of groups A-7 and A-6 is in their elasticity. Like group A-4, the A-7 soils vary in characteristics from those bordering on A-4 and A-5 silts and loams and the A-6 group of clays to those approaching the lower limits of group A-8 which contain excessive organic material. Such border-line soils are often designated as A-7-4, A-7-8, etc., indicating similarities to the latter groups. Where low temperatures prevail these soils should be given special consideration because some of them are subject to frost heave.

Group A-8.—These are composed of very soft peat and dirt and contain excessive quantities of organic matter and moisture. They are incapable of supporting a road surface without settlement and are unsuitable for fills and foundations. Their use in any type of construction should be avoided whenever possible. The grading is not significant.

Thicknesses of Sub-base, Base Course, and Surfacing.

This information is shown on the last line of *Table* XX and represents the maximum and minimum thickness of sub-base and road slab (base course and surfacing) required for each type of soil. These thicknesses were arrived at by observation and not by test and are the experience of many engineers.

The combined thickness of the sub-base composed of selected material, base course, and surfacing for each soil type as shown in *Table* XX will vary with variations in the soil constants, in the degree of compaction obtained, in the climatic conditions, and in the natural soil moisture. For example, a soil of group A-6 with a plasticity index of 20 and a natural moisture content of 18 per cent. will require less cover than an A-6 soil with a plasticity index of 50 and a natural moisture content of 30 per cent. When used in a dry climate, and where the depth to ground-water level is great, the first soil—(plasticity index 20)—will require less cover than where the groundwater level is high and the moisture content greater throughout the year due to high continuous rainfall. The thickness selected will depend on the judgment of the engineer. The selected material for the sub-bases may be composed of soils similar to those of groups A-1, A-2 and A-3 ; these are natural gravels which are stable but contain clay of such characteristics or quantity that they are not entirely suitable for use in base courses.

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ACKNOWLEDGMENTS

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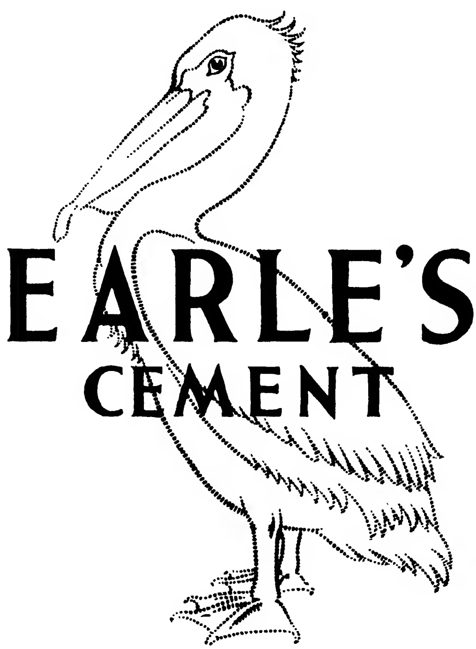

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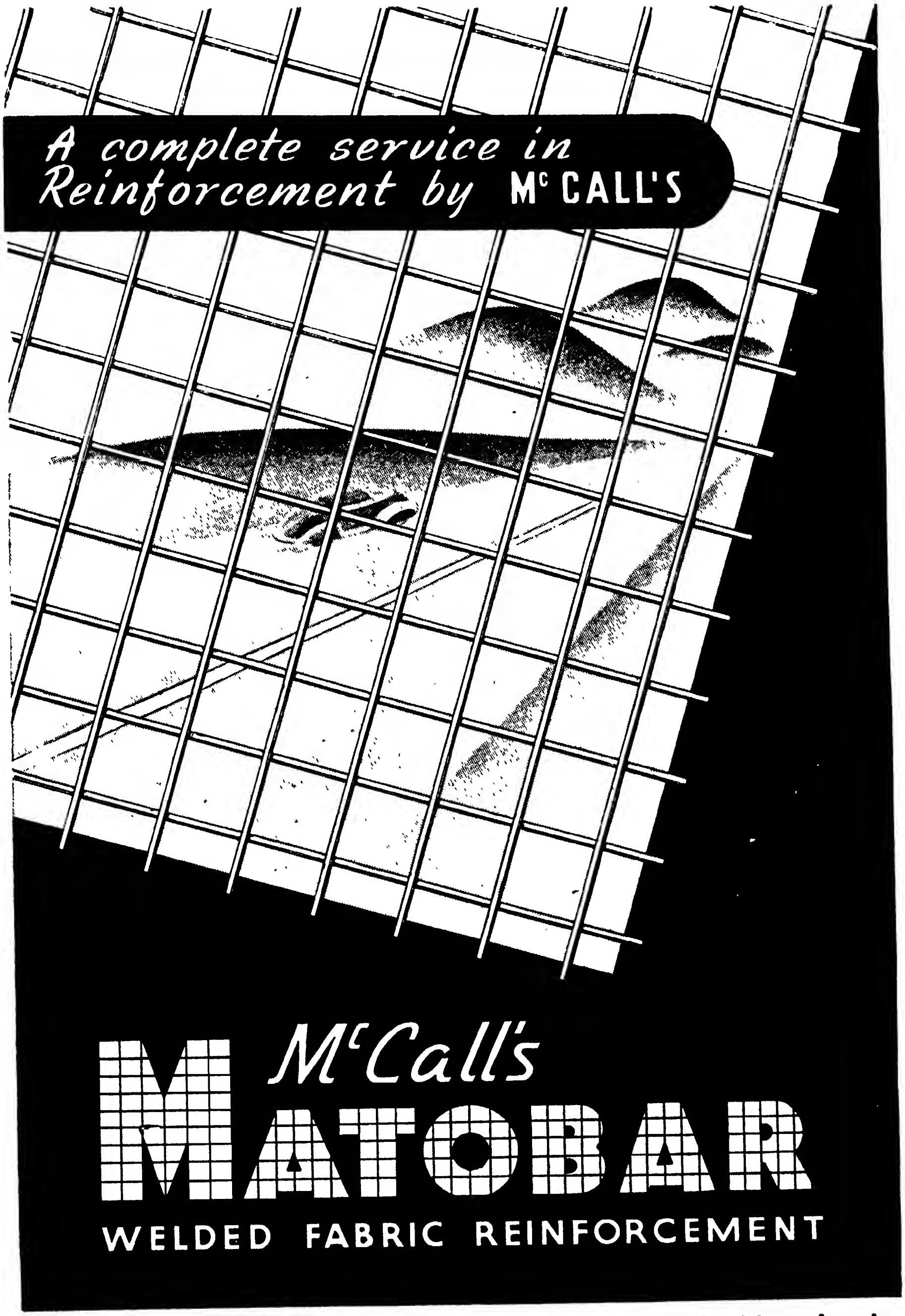
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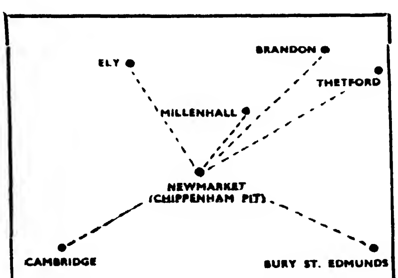

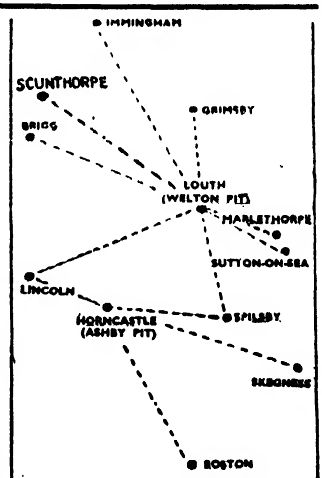

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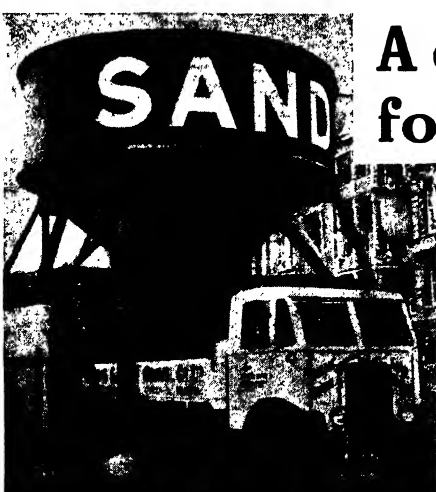

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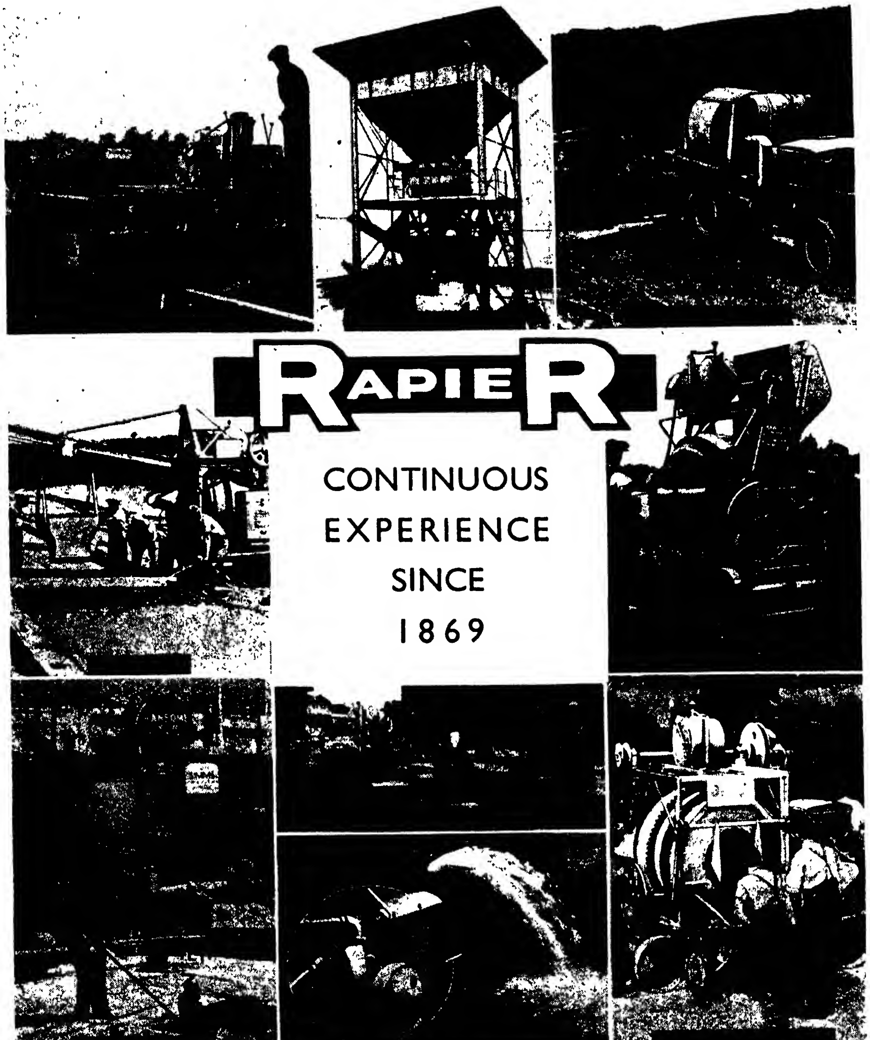

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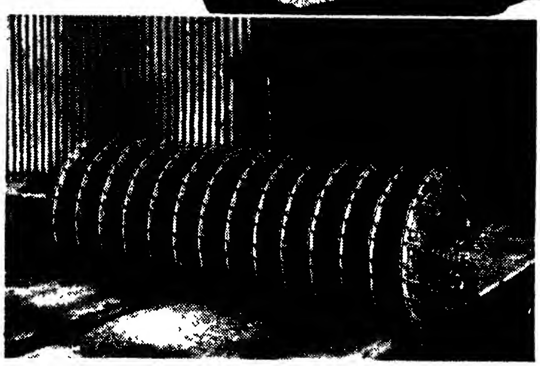

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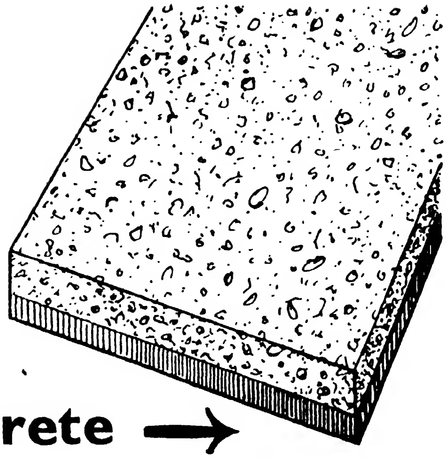

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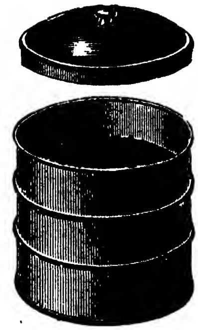

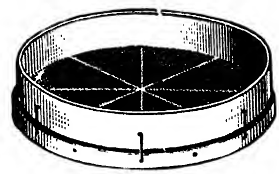

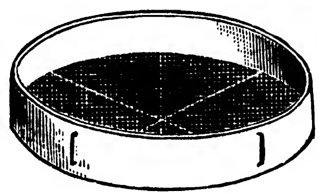

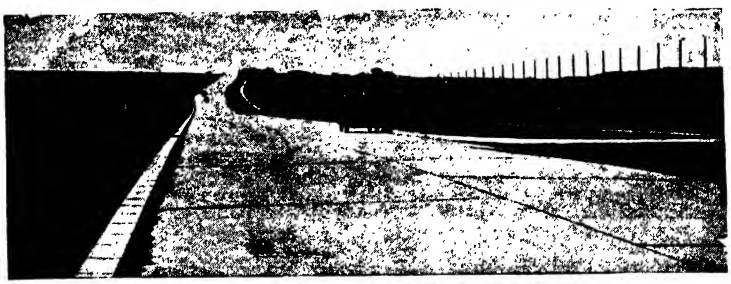

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