STUDY OF STRUCTURAL CHARACTERISTICS OF NATURAL FIBRE REINFORCED CONCRETE

THESIS

Submitted in partial fulfilment
of the requirements for the degree of

DOCTOR OF PHILOSOPHY

By

RAFAT SIDDIQUE

under the supervision
of **Dr. R.N. SAHAY**

BIRLA INSTITUTE OF TECHNOLOGY AND SCIENCE
PILANI (RAJASTHAN) INDIA

MAY 1993

DEDICATED

TO

MY FATHER

SHRI MOHUMMED SIDDIQUE

TO WHOM I OWE EVERYTHING-
WHATEVER I AM AND WHATEVER I HOPE TO BE

BIRLA INSTITUTE OF TECHNOLOGY & SCIENCE

PILANI RAJASTHAN

CERTIFICATE

This is to certify that the thesis entitled "STUDY OF STRUCTURAL CHARACTERISTICS OF NATURAL FIBRE REINFORCED CONCRETE" and submitted by RAFAT SIDDIQUE ID. No. 89PHXF401 for award of Ph.D. Degree of the Institute, embodies original work done by him under my supervision.

Signature in full of the supervisor

Name in capital block letters: Dr. **R. N. SAHAY**

Date: May 13, 1993

Designation: Visiting Professor

ACKNOWLEDGMENT

It gives me immense pleasure to put on record my over-whelming and everlasting sense of gratitude and indebtedness to my guide Dr. R. N. Sahay, formerly Director of Bihar Institute of Technology, Sindri (Bihar), presently Visiting Professor, B.I.T.S., Pilani, for his exceptionally pains-taking scrutiny, highly valuable tips, and continuous encouragement and inspiration, enabling me to successfully bring out the work in the present shape. Indeed it was a rare privilege to have worked under his experienced and innovative guidance.

I am also grateful to Dr. S. Venkateswaran, Director, B.I.T.S., Pilani and Dr. L.K. Maheshwari, Dean, Research & Consultancy Division of the Institute, for their magnanimity in allowing me the opportunity to undertake this investigation, utilizing unrestrictedly whatever facilities the Institute could offer for the purpose.

I would also like to take this opportunity of thanking Prof. I. J. Nagrath, Deputy Director, B.I.T.S., Pilani for his continued encouragement and inspiration for achieving academic excellence ever since I joined the Institute as M.E. student in Jan' 1988 as also during the course of this investigation.

My profound gratitude is also due to Late Dr. A. Dutta, Scientist, C.B.R.I., Roorkee, who despite his most compelling pre-occupation could find time to offer a number of useful and wholesome suggestions during the course of investigation, besides extending necessary lab. and library facilities.

I must acknowledge with deep sense of gratitude the timely help, assistance and solace I received from Prof. K. E. Raman, Workshop Unit Chief during the difficult and distressing period of this investigation. I also sincerely thank Dr. V. N. Sharma for his immensely valuable and thought-provoking hints relevant to this field of research. I must also thank Dr. K. R. V. Subramanian, Chief, D.L.P. Unit for his unstinted moral support in this matter.

My most heart-felt thanks are also due to Shri Satvir Singh, C. R. Rao of Workshop Unit, and Shri N. K. Soni of Material Testing Lab. for all the valuable help rendered by them in most unqualified manner.

I also wish to sincerely thank Mr. D. P. Soni for typing the thesis and Mr. K. N. Sharma for drawing the figures in a relatively much shorter period taking care of the time-constraints with me.

Thanks are also due to all my colleagues and friends in and outside the Institute for their suggestions, discussions and cooperation in the matter.

Last, but certainly not the least, I am grateful to my exceedingly loving and affectionate father and all my brothers and sisters, particularly elder sister Dr.(Miss) M. Z. Siddiqui, Technical Officer, I.V.R.I., Izatnagar, Bareilly (U.P.), who all along despite her heavy and ardous engagements continued to be a perennial source of inspiration, support and strength without which too, perhaps, the work would not have seen the light of the day.

RAFAT SIDDIQUE

ABSTRACT

An experimental investigation has been carried out to ascertain the strength and other characteristics of cement concrete reinforced with natural san (Crotolaria Juncea) fibre. San Fibre is a cheaply available material obtained from a plant which is extensively grown in many parts of Indian Sub-Continent. It is a bast vegetable fibre and is commonly used in India and its neighbouring countries for making twines and ropes etc.

Experiments carried out to ascertain the physical & mechanical properties of san fibre reveal that it has fairly good tensile strength and there is not much loss of its strength when treated in an alkaline medium of pH 11. It is durable in cement environment.

Reinforcing cement concrete with san fibre of suitable lengths and in proper proportions considerably improves split tensile strength, flexural tensile strength, energy absorption capacity, and impact strength. The experimental results when compared with corresponding calculated values obtained from a theoretical model show good agreement. Similar improvement was also found in respect of load-deflection characteristics of cement concrete beams reinforced with san fibres of suitable lengths and proper proportions.

Experiments carried out to ascertain the strength characteristics of conventionally reinforced concrete beams further reinforced with san fibres also showed positive results. Similar trend was also observed in case of concrete beams reinforced with san fibre twines, and also with san fibres together with twines. Compactability and mobility of plain concrete are however affected adversely by the presence of san fibres in the concrete. The most significant advantage of reinforcing cement concrete with san fibre is in regard to the growth of cracks emanating from natural flaws in cement concrete. San fibre is found to act as a good inhibitor of crack growth and thus can be expected to serve a useful purpose as a reinforcing material

CONTENTS

CHAPTER I

INTRODUCTION

CHAPTER III

DETAILS OF EXPERIMENTAL WORK

CHAPTER IV

PHYSICAL AND MECHANICAL PROPERTIES OF SAN FIBRE

CHAPTER V

MECHANICS AND PROPERTIES OF FIBRE REINFORCED CONCRETE

CHAPTER VI

COMPRESSIVE STRENGTH AND MODULUS OF ELASTICITY

CHAPTER VII

TENSILE STRENGTH

CHAPTER VIII

STRENGTH OF FIBRE REINFORCED CONCRETE SHEETS

CHAPTER IX

FLEXURAL BEHAVIOUR OF REINFORCED CONCRETE BEAMS

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

CHAPTER - 1

INTRODUCTION

1.1 General

Concrete is presently the most widely used construction material developed by man. Because of its speciality of being cast in any desirable shape, it has replaced stone and brick masonry. Inspite of all this it has some serious deficiencies which, but for its remarkable qualities of flexibility, resilience, and ability to redistribute stress, would have prevented its use as a building material.

Plain concrete is inherently weak in tension and has limited ductility and little resistance to cracking. Microcracks are inherently present in concrete and because of its low tensile strength, the cracks propagate with the application of load, leading to brittle fracture of concrete.

Microcracks in concrete are formed during its hardening stage. A discontinuous heterogeneous system exists even before the application of any external load. When the load is applied, microcracks start developing along the planes which may experience relatively low tensile strains, at about 30-40% of the ultimate strength in compression. Further application of the load leads to uncontrolled growth of the microcracks. The low resistance to tensile crack propagation in turn results in a low fracture toughness, and limited resistance to impact and explosive loading.

The low tensile strength of concrete is being compensated for in several ways, and this has been achieved by the use of reinforcing bars and also by applying prestressing techniques. Though these methods provide tensile strength to concrete, they do not increase the inherent tensile strength of concrete itself. Further, conventionally reinforced concrete is not a two phase material in true sense. Conventionally reinforced concrete is a true two phase material only after cracking when cracked matrix is held by the reinforcing bars. Existence of one phase (i.e. steel or concrete) does not improve the basic strength characteristics of the other phase and consequently the overall performance of the traditional reinforced concrete composite is dictated by the individual performance of the concrete and steel phase separately.

These deficiencies have led researchers to investigate and develop a material which could perform better in areas where conventional concrete has several limitations. One such development has been two phase composite materials i.e. fibre reinforced concrete, in which cement based matrix is reinforced with ordered or random distribution of fibres.

Fibre in the cement based matrix acts as cracks arrester which restricts the growth of flaws in the matrix, preventing these from enlarging under load, into cracks, which eventually cause failure. Prevention of propagation of cracks originating from internal flaws, can result in improvements in static and dynamic properties of the matrix.

The idea of mixing more than one materials to obtain a composite is not new. The two phase concept in which two materials are combined to produce a composite has been known since ancient times. The use of straw to strengthen sundried mud bricks and stabilize their dimensional stability, predates the use of portland cement.

Mortar and concrete are themselves essentially two phase composite systems in which relatively stiff aggregate particles are embedded in a soft brittle matrix imparting stiffness and stability to the composite. The behaviour of mortar and concrete indicates the role of fibre reinforcement of the cement matrix.

The idea that concrete can be strengthened by the inclusion of fibres was first put forward by Portar in 1910, but little progress was made in the development of this material until 1963 when Romualdi and Batson published their classic paper on the subject. Since then there has been a wave of interest in fibre reinforced concrete and several interesting experiments have been carried out. Several kinds of fibres such as steel, fibrillated polypropylene, nylon, asbestos, coir, jute sisal, kenaf, glass, carbon have been tried.

Various types of fibres as mentioned above have been developed and they are as follows.

1.2 Plastic Fibres

Plastic fibres such as nylon and polypropylene have high tensile strength, 5610-8670 kg/cm^2, but their low modulus precludes any reinforcing effect. However, their high elongation (15-25%), enables the composite to absorb 10 to 25 times more energy than unreinforced mortar and concrete. In applications requiring high energy absorption, plastic fibres have a special advantage.

The most successful form of polypropylene for use as fibre reinforcement is the fibrillated film fibres which are used extensively as reinforcement in piles and for non load bearing elements. Polypropylene is essentially a thermoplastic resin or polymer of the polyolefin family which softens when heated, and therefore does not possess a high temperature resistance. It has the advantage of chemical stability in the cement paste and is not attacked by acids and alkalis.

The most extensive use of polypropylene fibres is in concrete piles. The superior impact resistance properties of the fibres arises from purely mechanical bond between the fibre and the matrix. The fibres are made up from a number of fine fibrils, the matrix creeps and interacts among fibrils, and because of the absence of a physico-chemical bond, only minimum contact between fibre and matrix is necessary during mixing to ensure even distribution through out the mix. The reinforcing properties of the fibres are influenced by its diameter, the length of the fibre, the number of twists per unit length of twine, the amount of fibre content and its condition of mixing. Length shorter than 40 mm are found to shred in the mixer, and become ineffective as reinforcement. The degree of the mechanical bond achieved depends on the wire, the tightness of twist, the mixing time to give adequate dispersion and the abrasive action of the aggregate.

In addition to pile shells, polypropylene fibres are used extensively in non load bearing corrosion - proof members (under the trade name caricrete). In many conventional precast concrete components where steel reinforcement is incorporated purely for transportation and handling purposes, the use of plastic fibre can result in thinner, crack resistant sections, there by saving materials and reducing transportation and erection costs. It can be used in cladding panels, and in flotation units which are made by coating blocks of polystyrene with a layer of caricrete of 19 mm to 25 mm thickness. Fibres have also been successfully used in repairing a river wall by guniting, and as a crack inhibitor in forming artificial lakes.

1.3 Glass Fibres

Glass fibres are produced commercially in three basic forms, namely, ravings, strands and woven or chopped strand mat. The individual filament vary from 10 to 20 micron, and are coated with sizing to protect the fibre from surface abrasion as well as to bind them into a strand.

There are however, two main problems in the use of glass fibres in portland cement products, namely, the breakage of fibres, and the surface degradation of the glass by the high alkalinity of the hydrated cement paste. There are now several manufacturing processes that show promise of producing glass fibre reinforced cement products without the severe shattering of fibres associated with conventional asbestos cement manufacturing from chemical processes. To prevent the glass fibres from chemical attack, corrosion resistant coatings, usually resin based, have been applied, and after this, alkali-resistant glasses have been produced that appear to be satisfactory for use with portland cement. Fabrication techniques play an important part in the strength of glass-fibre reinforced elements. The use of a high water-binder ratio is essential so that the slurry can be worked, the excess water being removed by suction or pressing techniques.

While the spray suction technique produces a two dimensional random array of fibre reinforcement, conventional mixing with random dispersion of fibres can also be used. In both the techniques, glass fibre lengths of 10 to 50 mm can be used. Both these methods have been used to produce cladding panels, window frames, and other building and bridge components. There is considerable improvement in impact strength 20-25 X $10^3 J/m^2$ compared to 3-5 X $10^3 J/m^2$ for asbestos cement. It has also good resistance to thermal shock, and improved fire resistance which makes it usable as cladding or permanent shuttering for structural concrete. Long term modulus of rupture and impact strength test on GRC samples show that considerable improvement in durability can be achieved by the use of alkali-resistant glass compared with conventional E glass(Borosilicate). There is still a reduction in strength with time of storage in air, and a still greater fall when stored under water. However, such reductions in strength do not lead to total loss of strength. The use of high alumina cement and pulverized fuel ash in the matrix can further improve durability. The cheaper borosilicate or E glass has been extensively used with high alumina cement (Elkalite) and gypsum plaster without danger of alkali attack on the fibres.

Properties of these fibrous composites of interest and importance are: fire and chemical resistance, impermeability and water tightness. Several applications of high alumina cement and E glass have been tried such as grain silos, hollow pontoons for houseboats and heating units.

1.4 Steel Fibres

The third type of fibre that has found extensive engineering application is steel. Most of the steel fibres available for use in concrete are obtained by cutting drawn wires, and fibres with different types of crimps, indentations and shapes to increase mechanical bond are also being produced (e.g., Duoform). Steel fibres with lower tensile strength (7141 kg/cm^2) are also produced from low carbon flat rolled steel coils (e.g. Fibrecon). It has been shown that steel tensile strength has little influence on the first crack flexural strength, although it may have a significant effect on the ultimate flexural strength if the composite failure occurs by fibre failure rather than by fibre pull out. The efficiency of the fibre distribution depends on the geometry of the fibre, the fibre content, the mixing and compaction techniques, the size and shape of the aggregate inclusions and the mix proportions.

Steel fibre reinforced concrete material have been used for overlays and overslabbing for roads, pavements, airfields, bridge decks, and industrial and other flooring, particularly those subjected to wear and tear, and chemical attack. Guniting has been successfully applied with steel fibres.

1.5 Carbon Fibres

Carbon fibres have high tensile strength and young's modulus, but also a high specific strength compared to steel and glass fibres. Carbon fibre reinforced composite has linear stress-strain characteristics, and appears to possess adequate fatigue resistance and acceptable creep. Increase in flexural strength and stiffness are about 214.2 kg/cm^2 and 21420 kg/cm^2 respectively for the one percent of fibre.

Carbon fibre composites have shown 20 percent reduction in strength over a period of one year, when cured continuously in water at 50^0. With about 4 percent volume fraction of continuous unidirectional aligned fibres, CFC has about 1.5 times the modulus of elasticity of the matrix.

At low fibre fractions, the fracture toughness of CFC is low and not much higher than that of the matrix and is considerably lower than that of GRC. Test results show that a combination of carbon fibres with other fibres shows a substantial improvement in impact resistance.

Table 1.1 gives typical properties of plastic, glass, steel and carbon and other fibres.

Table 1.1

Typical Properties of Fibres

Type of fibre	Tensile strength, N/mm^2	Young's modulus N/mm^2	Ultimate elongation per cent	Specific gravity
Acrylic	209.1-423.3	2112.0	25-45	1.1
Asbestos	561.0-984.2	81.60-142.8 X 10^3	0.6	3.2
Cotton	423.3-703.7	51 X 10^2	3-10	1.5
Glass	1020.0-4081.0	71.41 X 10^3	1.5-3.5	2.5
Nylon	765.0-867.0	40.80 X 10^2	16-20	1.1
Polyster	739.4-882.2	81.60 X 10^2	11-13	1.4
Polyethylene	708.9	142.8-428.4	10	0.95
Polypropylene	561.0-705.0	35.71 X 10^2	25	0.90
Rayon	423.3-632.4	71.41 X 10^2	10-25	1.5
Steel	280.5-4233.0	204.0 X 10^3	0.5-3.5	7.8

1.6 Natural Fibres

Various types of natural fibres such as Sisal, Coconut, Bamboo, Jute, Flax, Akwara, Elephant-grass, Watereed, Plantain, Musamba, Maguey, Lechuguilla, Kenaf etc. are available.

The natural fibres are basically of four types.

1. Bast or Stem fibres (e.g. Jute, Flax, Kenaf)
2. Leaf fibres (e.g. Sisal)
3. Fruit hair (e.g. Coir)
4. Wood fibres (e.g. Bamboo)

A brief description of various natural vegetable fibres is presented here.

Elephant grass

Elephant grass is found near-by water courses and is common in sandy soil conditions. Its length is between 2 to 3 meter, but most common length being 2.4 meter. The diameter at the base is around 18 to 22 millimeter. The stem, which is not hollow but contains a pith made of soft fibres, is pale or dark purple. Load bearing stems of the plant are packed with fibres arranged parallel to each other in a matrix of lignin. The crust is thin and fibrous and fibre itself is tough and sharp, so that extraction by hand is not easy. It is available in India.

Water Reed

It is commonly found on the banks of lakes and streams. It grows in bushes and its height is between 2 to 3 meter. When it is mature, diameter of the stem may be as much as 20 millimeter. The stem consists of an empty interior and a strong fibrous crust about 5 mm thick.

Plantain

The trunk of this plant is fibrous and fibres can be easily extracted by hand. Fibres of the plant are strong and flexible. It is widely grown in India.

Musamba

This is a hardwood tree common to savannah lands. Its well known use is for making twines as ropes substitute. The bark of the tree is fibrous and extraction of the fibres is very difficult.

Akwara ,

Akwara has two shades of colors. The more matured and stronger end is dark brown, while other end is whitish. The fibre geometry is variable. The diameter varies from 1 millimeter to 4 millimeter and the length of the fibres is around 1.5 meter.

Maguey and Lechugulila

Both these fibres are of agave family. Both the fibres look identical. Their surfaces are covered by a natural substance like wax which if the fibres are placed in water would dissolve, producing a kind of foam similar to the commercial soap. The length of fibre varies from 30 to 50 centimeter.

Sisal

Sisal like other agave plants is tropical freshly leaved plant cultivated for its fibre. The fibre is used for cordage, rope etc.

Table 1.2 gives the typical properties of some of the natural fibres.

Table 1.2

Typical Properties of Natural Fibres

Fibre	Specific gravity	Tensile strength N/mm^2	Elongation at break %	Water absorption %	Modulus of elasticity N/mm^2
1	-	178.0	3.60	-	4936
2	-	70.0	1.19	-	5193
3	-	92.0	5.90	-	1436
4	-	83.0	9.70	-	941
5	1.24	390.0	0.50	65-70	-
6	1.36	390.0	0.50	95-105	22000
7	-	295.0	-	-	-
8	1.50	227.0	1.30	120	-
9	1.60	180.0	26.50	110	-
10	1.50	330-820	3.20	-	26000

1. Elephant Grass 2. Water Reed 3. Plantain 4. Musamba
5. Maguey 6. Lechuguilla 7. Kenaf 8. Jute 9. Coir 1o. Sisal

1.7 Need for Present Investigation

In India, use of fibres like steel, glass, carbon and polypropylene are not very useful because of their high cost of procurement due to the advantages claimed by them.

Nature has provided man with fibrous construction materials in the form of natural fibres. Natural fibres are produced in all countries. Their processing as compared to steel, glass fibres etc. require~~s~~ low degree of industrialization. The energy requirements and cost of their production is also very low. Further random mixing of fibres in cement or cement concrete requires semi-skilled personnel in construction work. This makes locally available natural fibres a very attractive material for improving and reducing the cost of cement concrete and related products. The relative cheapness of the natural fibres points the direction of their use and application on large scale as a building material in conjunction with concrete for housing and many other cost effective construction.

Present work envisages the use of naturally available San fibre as reinforcement in concrete as well as to understand the effect of San fibre on the properties of cement concrete, and reinforced concrete.

San fibre is extracted from the San plant which grows to about 1.0 m to 2.5 m in height and is light green in colour. The diameter of the plant varies from 10 mm to 30 mm. The stem of the plant is fully covered with a thin layer of fibrous skin, which can be removed from the stem in long longitudinal pieces, even at the green stage but with some difficulty. To make extraction of the fibres easy, the uprooted plants are placed under water for a period of 3 to 4 weeks, after which they are taken out of the water, the fibrous skin is separated easily. The fibres by this time are found to have acquired a light yellowish colour.

The san plants can be cultivated easily in most part of the country. The tropical climate in most parts of India and the soil available in plains ~~are~~ is very well suited for cultivation of this plant. Presently the San fibre is extensively used in the Indian villages for making ropes and twines etc. Picture of san fibre is shown in plate 1.1.

The present work was undertaken

1. To find out the physical and mechanical properties of the san fibre.
2. To study the effect of san fibre on the properties of cement concrete namely compressive strength. modulus of elasticity, indirect tensile strength, flexural tensile strength, load deflection characteristics of fibre concrete beams.
3. To find out impact and static strength of the plain and fibre concrete sheets.
4. To investigate the flexural behaviour of conventionally reinforced concrete beams with san fibres.
5. To study the effect of twines on the behaviour of concrete beams.

PLATE 1.1 SAN FIBRE

CHAPTER - II

LITERATURE REVIEW

In this chapter research work reported by several authors has been presented.

Romualdi and Batson[1] published in 1963 their classical paper on "Mechanics of crack arrest in concrete". They concluded that application of linear elastic fracture mechanics to reinforced concrete indicates that the relatively low tensile strength of concrete is not inherent to the material and can be avoided with suitable reinforcement arrangement. At appropriate spacings, incipient flaws are prevented from enlarging and propagating through out the tensile zone. The result is a true two phase material that exhibits strength properties not restricted by the characteristics of each separate phase.

Romualdi and Batson[2] concluded in their paper that the first crack strength of concrete improves by mixing closely spaced continuous steel fibres in it. These steel wires act as crack arresters preventing the advancing micro cracks by applying pinching forces at the crack tips and thus delaying the propagation of cracks. The existence of crack arrest mechanism in closely spaced wire reinforced concrete also suggests that such a material can be expected to offer high fatigue and impact resistance. They established that the increase in strength of concrete is inversely proportional to the square root of the wire spacing.

Romualdi and Mandel[3] have demonstrated that continuous steel wires could be replaced by randomly oriented small pieces of steel wires uniformly dispersed in the concrete matrix. They have shown that the spacing concept is equally applicable in this case also provided a correction factor is applied to account for the portion of the fibres not properly oriented for effective crack control.

Grimer and Ali[4] tried alkali resistant glass, developed at the building research station (U.K) , in concrete. They have shown that if given a durable glass fibre, the composites will have pronounced advantages of impact strength and resistance to cracking.

Shah and Ranjan[5] have shown that randomly distributed short steel fibres increases the ductility of the concrete by increasing its resistance against internal crack growth. They observed that the increase in volume of fibres increases the first cracking stress and for spacing less than critical, which is 2.5 cm for concrete made with 10 mm maximum size aggregate, spacing has less influence on the crack propagation than with spacing larger than 2.5 cm.

Rajagopalan et al.[6] carried out experimental work on the behaviour of fibre reinforced concrete in direct tension and flexure. Based on their study they concluded that closely spaced and well bonded steel fibres increase the strength of concrete beams both at first crack and at failure. The inclusion of fibres to the concrete imparts enormous ductility and large rotation capacity. Significant increase in flexural strength is obtained by the inclusion of fibres in the tension zone. They have presented empirical formula to predict the strength of fibre reinforced concrete beams.

Swamy[7] has given a systematic study of mechanics, properties and applications of fibre reinforced concrete.

Anon[8] reported the advantages of using fibrous concrete. Increase in tensile strength, flexural strength, first crack strength, impact and abrasion resistance have been reported. Data on properties like compressive ductility, higher fatigue, shear and torsion strength have also been presented.

Harris[9] has shown that the work of fracture is substantially increased for steel, glass, and carbon fibres in paste, mortar and concrete matrices. With steel fibres the interfacial bond strength is related to the aspect ratio and this has been shown to be an influential parameter in determining the fracture toughness of the concrete.

Swamy and Mangat[10] in their paper "A theory of the flexural strength of steel fibre reinforced concrete" have concluded that final failure occurs due to unstable crack propagation when fibres pull out and the interfacial shear stress reaches the ultimate bond strength.

Pokatiprapha et al.[11] in their paper, which was published in March 1974, have investigated the mechanical properties of the composite in flexure, torsion, axial compression and tension analytically by the application of the laws of mixture. Based on their study they found that the mechanical properties of the composite can be determined from the laws of the mixture with the mortar acting as the matrix and the short steel wires as fibre reinforcement. In bending the composite slab element behave as a two layered bilinear element.

The presence of steel fibres does not significantly influence the rupture strength of the matrix in bending. This is in agreement with the results obtained by Shah and Ranjan[16] but differs from those reported by Romualdi and Mandel[3]. However, steel fibres considerably increase the resistance of the mortar to crack propagation. The ultimate strength in axial compression of the composite is less than the ultimate strength of the mortar. However, the presence of the fibre increases the ductility of the composite. They further suggested that a stronger material could be obtained if the wires of smaller diameter and longer length were used, provided that the problem of bundling is overcome. The latter can be avoided by trial mixing as suggested by Romualdi and Mandel[3].

Tattersall and Urbanowicz[12] conducted tests to study the effects of various chemical and physical treatments of the wire surface upon the bond between a wire and a cement or mortar matrix. This was done by means of a simple pull out test. Galvanizing produced some improvements in bond, but the best results were obtained from a wire with a looped end and an indented wire. In both the cases, failure occurred outside the specimen at loads approximating to the ultimate tensile strength of the wire.

Hannant[13] describes a technique by which short steel fibres can be aligned parallel to the direction of tensile stress in mortar beams to be subjected to flexural loading. A combination of vibration and mechanical alignment enables the load carried by the beam to be doubled in compression with that achieved by using vibration table.

Kar and Pal[14] conducted studies on steel fibre concrete and have suggested certain equations for predicting tensile strength as a function of effective spacing. The results obtained are in agreement with the theoretical results reported by Romualdi and Batson[2].

Ramey et al.[15] have reported that the fatigue strength of fibre concrete reinforced with 1/2" long, 0.0058" diameter undeformed brass coated steel wires (2% by volume of mix) is of the order of 95 percent of the static strength. This is considerably greater than 55 percent usually associated with concrete fatigue tests.

Shah and Vijay Ranjan[16] investigated mechanical properties of concrete and mortar reinforced with randomly distributed smooth steel fibres. Different volumes, lengths, orientations, and types of fibres were used. Fibres were compared with conventional reinforcement in flexure tension and compression. It was observed that the significant reinforcing effect of fibres is derived after the cracks are initiated in the matrix. The post cracking resistance of fibres is considerably influenced by their lengths orientation and stress strain relationship. The spacing of reinforcement appears to have little influence on crack propagation below a certain length. The reinforcing action of fibres was analytically predicted by using the composite materials approach based on the properties of individual components.

Chen and Carson[17] have reported that tests conducted by them on standard cylinders in direct compression and indirect tension showed that mortar exhibited an optimum tensile and compressive strength with 0.75 percent of the 12.7 mm diameter fibre wire.

The concrete gave its best tensile (60% increase) and compressive strength at 2.0 percent of 25.4mm and 12.7 mm fibre wire and ductility was also increased. They further suggest that higher strengths and greater ductilities can be obtained by using different size wire and higher percentages of reinforcement.

Snyder and Lankard[18] investigated the effect of steel fibre parameters and concrete mix parameters on the flexural strength properties of steel fibrous concrete and mortar. They have reported that significant increase in the first crack flexural strength (upto three fold) and ultimate flexural strength (upto four fold) of mortar and concrete can be achieved through the use of short length (6.4 to 63.5 mm) having small diameter (0.15 to 0.79 mm) steel fibres. There exists a linear relationship between first crack flexural strength and ultimate flexural strength as a function of fibre content for (0.25 x 25.4 mm) fibres in mortars containing 4% fibres by volume.

Anon[19,20] studied the effect of fibre content and the aspect ratio of fibres on workability of concrete. It is reported that as the fibre content and aspect ratios are increased, the workability decreases rapidly. The problem of balling which seriously affects the workability and the uniform dispersion of fibres has been tackled by dispersing the fibres through a sieve shaker on to a conveyer from which they were blown into a reversing drum mixer.

ACI[21] has brought out a special publication (SP 44) to cover the proceedings of the symposium on fibre reinforced concrete held in Ottawa. The report covers in detail the properties and applications of the fibre reinforced concrete.

Shah, S.P.[22] gives a brief idea of different types of reinforcing materials. He discusses mineral fibres, organic fibres, metallic fibres, ferrocement and their comparison.

Johnston and Coleman[23] have reported a brief review of the different methods which can be used to compare the properties of the fibre and plain concrete. They have emphasized the importance of the method adopted, which influences the apparent cost performance.

A state of the art report on fibre reinforced concrete[24] was published by ACI Committee 544 in November 1973.

Gunasekaran[25] conducted tests to investigate the flexural strength and load defection behaviour of light weight concrete beams (150 mm x 150 mm x 900 mm) made with sintered fly ash aggregates and regulated set cement and included steel fibre reinforcement. Three different aspect ratio of about 47, 50 and 63 were used for the fibres. It was found that beams containing fibres with an aspect ratio of 50 had the best flexural strength 34.5 Kg/cm^2, but the beams containing fibres with an aspect ratio of 62.5 had better ductility, although lower flexural strength, 25.3 kg/cm^2. In both cases the quantity of fibres used was the same. Beams made with concrete having the same total quantity of fibres as before, but comprising 50 percent fibres with an aspect ratio of 62.5, and 50 percent with an aspect ratio of 50, possessed considerable ductility with out any reduction in flexural strength. They have concluded that for equal quantities of fibre reinforcement, a blend of fibres consisting of both long and short fibres results in greater structural benefits in concrete than identical fibres with a high aspect ratio, and low aspect ratio fibres act as crack arresters in the finite volume enclosed by the high aspect ratio fibres, the latter are primarily responsible for the enhanced ductility of fibre reinforced concrete.

Krishna Raju et al.[26] have reported the results of a laboratory investigation on the compressive strength and bearing strength of steel fibre reinforced concrete using three different grades of concrete with the fibre content varying from 0 to 3 percent. The ratio of the bearing area to the punching area was varied in steps within the range of 5 to 20. Test results indicated that the compressive strength and bearing strength of concrete increases with the percentage of fibre content. They have developed empirical formula on the basis of test results for the prediction of the compressive strength and bearing strength of fibre reinforced concrete.

Hale, D.K.[27] has examined the process of fibre pull out in multiply-cracked aligned discontinuous fibre composite and has shown that with fibres of uniform cross-section, pull out normally takes place preferentially at a single crack. He has analyzed and defined the conditions required for multiple pull out and uniform extension of the composite.

Swamy and Mangat[28] have reported that the composition of the matrix and its strength properties influence the fibre matrix interfacial bond stress and also the relative contributions of the matrix and the fibres to the composite flexural strength.

Swamy and Mangat[29] published a paper on the onset of cracking and ductility of steel fibrous concrete. They have tried four different methods for detecting the initiation of cracking. They have concluded that the most significant role of fibre reinforcement lies in increasing the post cracking properties of ductility, tensile strain capability and energy absorption capacity.

Krenchel, H.[30] studied the effect of fibre spacing on the behaviour of the composite. The average fibre spacing governs the rheological properties of the composite during mixing and also to some extent affects the mechanical properties of the finished products. The average spacing is calculated from the number of fibres crossing a unit area in any arbitrary cross-section of the composite. This number is taken to be a function of the cross-sectional area of the fibres and the fibre concentration and the type of orientation of the reinforcement.

Swamy and Mangat[31] have presented equations using a composite mechanics approach to predict the first crack and ultimate flexural strength of the concrete reinforced with short discontinuous steel fibres randomly oriented and uniformly distributed throughout the concrete mass. From these equations, design equations are derived which are sufficiently lower bound to be usable in practice. The equations are shown to be valid for a wide range of mix proportions, aggregate size and fibre geometry that is likely to be met in construction practice.

Hughes and Fattuhi[32] have concluded that the workability of the fresh fibrous concrete mix depends upon the properties and proportions of the constituents. Increasing the sand content and gravel content, and the volume fraction, aspect ratio and length of the fibres, and decreasing the fibre diameter and water/cement ratio of the mix, decrease the workability of the composite. The maximum size of the aggregate (10 or 19 mm) did not have a significant effect upon the workability for low coarse aggregate content concrete mix tested. The workability measured by the slump or vebe consistometer methods showed single relationships for a particular mix which depends only upon the fibre properties. These relationships can be useful when fibrous mixes are being designed.

Hughes and Fattuhi[33] examined the effects of the addition of various fibres including fibrillated polypropylene as well as round straight duoform, crimped and hooked steel on the compressive stress strain properties of concrete matrix. They concluded that the addition of polypropylene fibres decreased the density, dynamic modulus of elasticity and the compressive strength of concrete, but enhanced its ductility. The maximum increase observed in the compressive strength of the concrete of nearly 7% was achieved by the addition of 0.25 x 25 mm duo-form steel fibres. They have further mentioned that the strength and the initial slope of the stress strain curves for all the fibre mixes increased slightly with age and are generally similar in nature.

Frondistou[34] conducted experiments to test the accuracy with which the theoretical model of Pakotiprapha et al.[11] originally developed for steel fibres reinforced concrete, can predict an extensive published flexural strength data for concrete reinforced with glass fibres. He has concluded that the comparison of theory with experiments shows agreement well within 15%.

Kasperkiewiez[35] presented a method which makes it possible to evaluate the fibre content or to estimate the distribution of fibres in steel fibre reinforced composite materials from the analysis of X-ray pictures. The basic notion in the method is an apparent fibre spacing defined as the average spacing between the intersections of individual fibre projections upon a certain plane and an arbitrary base line drawn on that plane. Such apparent spacing may be estimated analytically, which can also be measured directly on the radio gram. Analytical and experimental data show satisfactory agreement.

Komlos^{36} conducted tests to find out uniaxial tensile strength of concrete reinforced with A-fibres (Slag-basalt fibres) and glass fibres at the age of 0, 3 and 6 hours and obtained relationships between the fibre volume fractions and uniaxial tensile strengths of concrete at different ages. He showed that the kinetics of strength increase is to a high degree dependent on the kind of fibre reinforcement.

Swamy and Stavrides^{37} have reported that the properties of fibre reinforced composites are largely determined by the method of fabrication. With steel fibre concrete, geometry of the fibre, the method of casting and compaction and compactability of the fibre concrete mix, all significantly influence the disposition of the fibres in the hardened composite. Tests on fibre concrete mixes with adequate flowability characteristics showed that apart from these factors, the size, shape, and surface texture of the aggregates, all very much affect not only the fibre orientation but also the fibre distribution during the manufacturing process. The degree of compaction as measured by the solidity of the compacted concrete is influenced both by the method of compaction, and when vibrated, by the duration of vibration. Internal vibration increased compressive strength marginally compared to external vibration, but the latter increased the flexural strength substantially compared to internal vibration. The effect of vibration was more pronounced with dry mixes. Increasing the size and the roughness of the surface texture of the aggregates reduced the flexural strength by as much as 25%. Vertical casting reduced not only flexural strength but also the capability of the fibres in resisting stress in the post cracking stages. Loading in the "as cast" direction produced a small, but noticeable increase in flexural strength but negligible effect in compression. Round and smooth aggregates encouraged fibre settlement in the bottom half of the "as cast" section but this was counteracted by larger aggregate sizes crushed aggregates and higher fibre volumes. The results showed that good mix design and external vibrations are necessary to optimize the performance of the fibre.

Samarrai and Elvery[38] investigated the possibility of incorporating steel fibres in steel reinforced concrete to retard the development of cracks so that steel of higher strengths can be used in the concrete. They tested 75 x 75 x 500 mm concrete prisms in uniaxial tension applied to the protruding ends of the concentrically placed reinforcing bars. The inclusion of steel fibres in the concrete significantly increased the stress in the reinforcement corresponding to the development of the maximum allowable crack width in concrete.

Hughes and Fattuhi[39] proposed bond tests for single fibre or grouped fibres of various shapes, diameters and lengths.

Schnutgen, B.[40] has proposed a theory for evaluation of the influence of steel fibres on the tensile strength of steel fibre reinforced concrete. The theory is based on the assumption that the theory of crack propagation is applicable as in case of quasi-brittle material. The expression obtained numerically shows good correlation with the experimental results.

Naaman and Shah[41] have reported that the efficiency of fibre orientation for steel fibre reinforced concrete can not be predicted from static continuum considerations. This is because the fibre contribution in such brittle matrices is significant only after matrix cracking and because the pull out mechanism of inclined fibres is substantially different from that of aligned fibres. They have shown that pullout resistance calculated from the pullout test of a single fibre does not always correspond well with the fibre contribution in the composite where a group of fibres are simultaneously pulling out from cracked surfaces.

For a large number of fibres the fibre contribution depends significantly on the capacity of the matrix to withstand the forces enclosed by the fibres bridging the cracked surfaces. They observed that spalling and disruption of the mortar matrix lead to a substantial reduction in the pull out resistance. To increase the efficiency of the steel fibres in concrete matrices it seems necessary to increase both the bond properties of the fibre and properties of the matrix.

Uzomaka[42] has reported some relevant physical characteristics of akwara and akwara reinforced concrete. Based on the test results he concluded that akwara is dimensionally stable in water and appears durable in cement matrix environment. The stress-strain relationship is linear and the apparent initial tangent modulus is of the order of 2 KN/mm^2. Akwara reduces compactability, mobility of freshly mixed concrete and does not affect uniaxial compressive strength or modulus of rupture. Akwara enhances the impact resistance of a mix, a 5% fibre volume content results in improvement in impact resistance of between 5 and 16 times that of the unreinforced counterpart.

Lewis and Mirihagalia[43] conducted tests on mortar reinforced with natural fibres like water reed, elephant grass, plantain and Musamba. Based on the test results they concluded that among the four fibres elephant grass showed the greatest promise as a reinforcing material. Elephant grass has a tensile strength of

180 N/mm^2, a modulus of elasticity of 5 KN/mm^2 and is not adversely affected by alkaline and rotting environment. Elephant grass fibres improve the flexural and impact strength of cement sheets.

Dinesh Mohan and Rehsi[44] have reported in their published paper that an attempt is made to improve the strength and structural performance of cellular concrete units and doubly curved concrete tiles developed by CBRI, Roorkee, by incorporating steel fibres having an aspect ratio of 75 and of 0.5 percent by volume of concrete. The results show that the steel fibre reinforced units developed 20% higher strength at 28 days as compared to the corresponding unreinforced units.

Mangat[45] has concluded that the standard law of mixture rule can be successfully modified to determine the tensile strength of concrete reinforced with short steel fibres of length less than the critical one. Experimental results on circular and rectangular fibres show good correlation with the theory. He also concluded that the relation between effective spacing and tensile strength is non-linear decreasing with increasing effective spacing.

Kukreja, C.B. et al.[46] have reported that tests were conducted to compare the direct tensile strength, indirect tensile strength and flexural tensile strength of the fibrous concrete with that of plain concrete. They used fibre obtained by cutting the wires on a hand operated machine in three lengths 46mm, 36.8mm and 27.6mm having aspect ratio of 100, 80 and 60 respectively. They observed that the percentage increase in the direct tensile strength is directly proportional to fibre concentration for a constant aspect ratio. Maximum increase of 46.33 percent was obtained with fibres of aspect ratio 80 with 1% volume concentration and the maximum increase in indirect tensile strength is 40% for fibres having aspect ratio 80 and volume percentage of 1.5%. Flexural strength increases by 46.15% for fibres having aspect ratio 80 and volume percentage 1.5.

They have concluded that indirect tensile cracking stress is an inverse function of fibre spacing and fibre reinforcement is more effective in improving the post cracking strength than the first cracking strength of the composite. They have further added that the energy absorption capacity of the fibrous composite in flexure increases by 14.98 times due to addition of fibres of aspect ratio 80 and volume concentration 1.5% over plain concrete composite.

Walkus et al.[47] studied the cracking behavior strength properties and deformations properties of tensile specimens of concrete reinforced with short steel fibres. They noticed that the addition of cut steel fibres to the concrete increases its strength but only upto some critical amount of micro reinforcement (ie; 1.2% to 1.8% by volume). A volume of steel fibres of about 1.2% seems to be the best. The influence of micro reinforcement arrangement on cracking behaviour was analyzed on the basis of x-ray photography. It was observed that the location of cracks depends on orientation and number of fibres in the cross-section.

Castro and Naaman[48] used natural fibres Lechuguilla and Maguey of agave family as reinforcement in cement mortar. Based on their study they concluded that natural fibres of the agave family have tensile strengths upto 552 MPa and elastic moduleus upto 3 x 10^6psi. They did not observe any significant difference in either mechanical properties or the reinforcing efficiency of Maguey or Lechuguilla fibres. Lengths of fibres upto 75 mm and volume fractions upto 11 percent can be mixed with portland cement mortar matrix. To achieve this higher water content and / or the use of superplasticizer are necessary to get such limits under normal conditions. Elasto-plastic behaviour in flexure and multiple matrix cracking were achieved for volume fraction of fibres above 7%.

ACI committee 544[49] published a report on the measurement of properties of fibre reinforced concrete. The report gives a review on the existing test methods and suggesting new methods where necessary. New testing methods are suggested for (1) toughness energy absorption (2) impact strength (3) workability. The applicability of the existing test methods to fibre reinforced concrete are reviewed for air content, yield, unit weight, compressive strength, split tensile strength, shrinkage, creep, modulus of elasticity, cavitation, corrosion and abrasion resistance.

Ramakrishnana, V. et al.[50] have presented a comparative evaluation of two types of steel fibres used as reinforcing materials in concrete. The fibres used were 25.4 mm long straight fibres and 51mm long fibres with deformed ends which were glued together into bundles with water soluble adhesive. They conducted tests for (1) flexural fatigue (2) static flexural strength including strain, deflection, modulus of rupture, load deflection curves, determination of first crack load, and determination of post cracking strength of two sizes of beams (3) impact strength to first crack and ultimate failure (4) compressive strength and (5) plastic workability including vebe slump and the inverted cone time immediately after mixing and after one hour. The complete series of tests ~~was~~ were run for two concentrations of the collated and hooked fibres and with pozzolan and straight cement mixes. The workability and handling of the plastic hooked fibre mix with 80 lb/yd^3 was good, while the higher fibre content restricted the workability of this mix.

Based on the experimental investigation they concluded that no balling of fibres occurred in the case of hooked fibres even though they were dumped into the mixes all at once along with the aggregate. The compressive strength of the fibrous concrete is slightly higher than the compressive strength of plain concrete mix. The static flexural test shows that an excellent end anchorage is established between the hooked fibre and the matrix, resulting in a high ultimate flexural strength, high load carrying capacity and high ductility of the composite material. The hooked fibre reinforced concrete shows a greater ability to absorb impact loading than straight fibre reinforced concrete.

For the two hooked fibre concentrations used, no significant difference was recorded in the ultimate flexural strength, post cracking load carrying capacity and ductility. However, impact resistance and toughness increased with increased fibre content.

Swamy and Al Taan[51] have presented an extensive experimental data on the deformation characteristics and ultimate strength in flexure of concrete beams made with 20mm maximum size of aggregates and reinforced with bar reinforcement. Fibres were provided either over the whole depth of the beams or in the effective tension zone only surrounding the steel bars. It was shown that ultimate strength is increased only marginally, the fibres arrest cracks and increase post cracking stiffness at all stages of loading up to failure which results in narrow crack widths and less deformation. The tests showed that at failure the compressive strains reached values of 0.005 to 0.006 and reinforcing bars attain stresses well in excess of their yield strengths. They further proposed an ultimate strength theory which shows good agreement with the experimental data.

Barr and Mohamad Noor[52] have proposed an alternative definition of toughness index. According to them, toughness index can be obtained from the load deflection graph and is given by the ratio of the area under the graph (at the point of two times the deflection at first crack) divided by four times the area under the graph at the point of first crack. They have presented toughness index results which were obtained from three notched test specimens geometries : compact compression, notched beam and compact tension test specimens. Based on the study, they concluded that results for toughness were independent of both geometry and notch depth and the toughness index of steel FRC increased by 100 % as the fibre content was increased in the range of 0.03 to 0.9% by volume.

Panella and Naaman[53] have reported a comprehensive experimental and analytical evaluation of the stress strain properties of fibre reinforced mortar (concrete) in compression. They used three fibre materials (steel, glass, polypropylene) , three volume contents and for steel fibres three aspect ratios in combination with three mortar matrices of increasing compressive strength. They analyzed the influence of these parameters on the peak stress and strain, the shape of stress strain curve and the toughness of the composite.

Ramakrishnan et al.[54] have presented a review of all the important analytical models published till June 1987. They have discussed the merits and limitations of all the models in their application to fibre concrete composites.

Shah[55] in his paper has examined the in-elastic response of the fibre reinforced composites using a micro mechanical model, a linear elastic fracture mechanics model for the pullout fracture and a nonlinear fracture mechanics model for predicting the post peak response.

Khan T. A.H. et al.[56] made a behavioural study of steel fibre reinforced concrete under compression, indirect tension and compression, indirect tension and pure flexure. Variables adopted in the experiments were fibre length, diameter and fibre volume. Some of the test data were examined in the light of the composite material theory and spacing theory. The spacing varied through the volume fraction of the fibres was found to have an effect over the tensile strength of SFRC while the spacing varied through fibre diameter was seen to have little effect. Test data were also analyzed in view of some established relationships between different strengths of SFRC like the cube strength, split cylinder strength and modulus of rupture.

Paramasivam et al.[57] have presented an idealized stress strain curves for steel fibre reinforced concrete and reinforcing steel and suggested simplified analytical expressions for moment curvature and load deflection behaviour of simply supported reinforced steel fibre concrete beams in flexure. Analytically predicted moment-curvature and load-deflection curves for test beams were found to agree well with the experimental data. The reinforced steel fibre concrete beams showed higher flexural strength and curvature ductility at ultimate load when compared to similarly reinforced plain concrete beams. They concluded that the approach suggested is a useful tool in the analytical study and design of reinforced steel fibre concrete.

Nagarkar et al.[58] conducted tests on concrete reinforced with steel and nylon fibres. They concluded that in general the compressive strength is increased by 5 to 57% with the addition of fibres. However, this increase is more prominent in case of steel fibres than nylon fibres. The split tensile and flexure strengths are increased by 15 to 45% and 20 to 60% respectively.

Corradini et al.[59] have discussed in their paper the statistical evaluation of the effects of cement content, Water/cement ratio and fibre content on 28 days compressive strength, tensile strength, secant modulus of elasticity, first crack moment and failure bending moment of a steel fibre reinforced concrete. The statistical approach was adopted both to design the tests and to interpret the results obtained. The work has been performed on the basis of a factorial experiment programme. Tenacity index and the ratio of the fibrous concrete strain work to the matrix strain work were determined.

Achyutha and Sabapathi[60] have presented results of an experimental investigation on the effects of inclusion of steel fibres in conventionally reinforced concrete beams on their cracking characteristics. They concluded that load at first visible crack increases by 50 to 128% due to inclusion of steel fibres over the whole section of a reinforced concrete beam. But the increase is of the order of 30% only in the beams with fibres around the tension steel only , compared to beams without fibres and beams with extra reinforcement equivalent to the quantity of fibre around tension steel. The presence of fibres reduces the crack height by 25%. There is a reduction of 50 to 90% in the maximum crack width at working load depending upon the fibre aspect ratio. The effect of fibres on maximum or mean crack spacing has been found to be insignificant irrespective of the fibre aspect ratio and volume percentage. The general trend is that an increase in the fibre content and aspect ratio enhances the percentage increase in load at a specified crack width.

Ramakrishnan and Josifok[61] have presented the results of an experimental investigation to determine flexural fatigue strength of concrete reinforced with deformed (corrugated) and melt extract steel fibres. They conducted tests on flexural fatigue and endurance limit static flexural strength including load-deflection curve, determination of first crack load, toughness index, compressive strength, static modulus, pulse velocity and unit weight, and workability of fresh concrete. They concluded that there was no balling or tangling of the fibres during mixing and placing. Fibre reinforced concretes had better finishability and were easy to work with even at higher fibre concentration. Due to the addition of fibre , the ductility and the post crack energy absorption capacity were greatly increased. There was a tremendous increase in the static flexural strength and a very significant increase in the flexural fatigue strength. There was a considerable improvement in the endurance limit over plain concrete.

Kukreja et al.[62] have reported that two way reinforced fibre concrete slabs have been tested for various volume percentages of fibres and with an optimum aspect ratio of 80. They concluded that the first cracking strength and ultimate strength of reinforced fibre concrete slabs increases with the increase in fibre content. The maximum increase in first cracking and in ultimate strength is 35% and 80.92% respectively. The deflections at serviceability limit state in reinforced fibre concrete slabs are about 21% lesser with fibres having aspect ratio 80, and volumetric percentage of 1.5, whereas the deflections at failure loads in reinforced fibre concrete slabs are nearly 2 times that of deflections in slabs without fibres. Crack widths at limit state of cracking in reinforced fibre concrete slabs get reduced by 36%.

Srinivas et al.[63] have presented the basic principles of ultrahigh strength (1650-2000 N/mm^2) steel fibres and their suitability for concrete reinforcement.

Dwarakanath and Nagaraj[64] studied the effect of presence of steel fibres in conventionally reinforced concrete beams and observed that the partial inclusion of the fibres over half the depth in case of under reinforced beams, is usually as beneficial as the full depth inclusion.

Halvorsen and Kesler[65] have reported that the failure of steel fibre reinforced concrete beam is typically characterized by cracking of the matrix followed by pull out of the individual fibres. To compare the behavior of concrete reinforced with plain and deformed steel fibres, moment curvature relation-ships were determined experimentally for flexural specimens 100 x 150 x 1625 mm. Two fibre contents with each of six fibre geometries were used. The result indicate that post cracking resistance may vary considerably depending on the fibre ductility and failure mode of individual fibres, as well as fibre content.

ACI Committee 544[66] has ~~have~~ published a guide for specifying, mixing, placing and finishing steel fibre reinforced concrete. This guide describes the current technology in specifying, mixing, placing and finishing of steel fibre reinforced concrete (SFRC). The emphasis in this guide is on the differences between conventional concrete and SFRC and on how to deal with them. Guidance is provided in mixing techniques to achieve uniform mixtures, placement techniques to assume adequate compaction, and finishing technology to assume satisfactory surface texture.

Nagaraja and Swamy[67] performed tests on specimens (reinforced with non metallic fibres) to determine the compressive strength, split tensile strength, flexural strength, energy absorption and modulus of elasticity. The results show that addition of non-metallic fibres do not contribute to the improvement of compressive strength compared to plain concrete. The tensile load carrying capacity of FRC is fairly increased over that of plain concrete. Non-metallic fibres also contribute towards increased resistance to impact and blast.

Islam Rafiqul and Alam Khorshed[68] investigated the effect of introducing various percentages and length of different types of chopped fibres of jute and coconut into concrete and their effects on compressive and tensile strength of concrete. Results showed that the addition of jute and coconut fibres to the concrete, decreases the compressive strength but slightly increases the tensile strength.

Kukreja and Chawla[69] published their paper on "flexural characteristics of steel fibre reinforced concrete". They used three shapes of fibres, viz. straight, bent and crimped with varying volume percentages, viz. 0.5, 1.0 and 1.5, aspect ratio being the same as 80 in all the cases. Based on their study they concluded that the flexural strength alone does not adequately describe the behavior of fibrous concrete. Depending upon steel fibre content, its type and orientation, behavior can range from brittle to very ductile, all for the same range of flexural strength. Flexural stiffness of the fibrous concrete is higher than that of ordinary concrete, emphasizing the ability of the fibres to arrest cracks due to the bridging action of fibres.

Pomeroy, C.D.[70] has presented the principal effects of fibres of various types and of polymers upon the properties of portland cement pastes, mortars and concretes. He has concluded that reinforced and prestressed structural concretes are unlikely to be replaced by fibre or polymer concretes.

Sabapathi and Achyutha[71] have presented a flexural theory for the analysis of steel fibre reinforced concrete beams in post cracking range based on the load slip curves obtained from the pull out tests of fibres. Modulus of rupture or ultimate moment values of SFRC beams, based on the proposed theory are found to be in good agreement with the present experimental and some of the earlier investigations.

Colin and Johnston[72] examined the performance of steel fibre reinforced concrete under flexural fatigue loading in terms of fibre content (0.5 to 1.5 percent by volume), fibre aspect ratio (47 to 100), and fibre type (four types). They conducted 194 fatigue tests and 135 complementary static loading tests.

Gopalaratnam et al.[73] carried out work in the first phase of a six university study. First phase included specimen size, fibre volume content, fibre type, and effect of a notch as the primary parameters of investigation . They presented results including toughness and other parameters like stress at first crack, ultimate strength, and elastic modulus.

Ezedin and Steven[74] have presented an experimental program designed to study the mechanical properties of rapid set materials reinforced with steel fibres. The primary variables used in the study were a) rapid set cementing materials b) fibre type and c) fibre content. Three commercially available rapid set materials and four fibre types made of low carbon steel were incorporated in the study. Out of the four fibre types two were hooked at the ends, one was crimped at the ends and one was crimped throughout the length. Steel fibres were added in quantities of 50, 75, 199 lb/yd.^{3} Based on the experimental investigation they concluded that steel fibres can be successfully mixed with rapid set materials up to a quantity of 75 lb/yd.[3] They reported increase in the compressive strength, first crack strength and flexural strength.

Kosa et al.[75] have reported the comparison of the durability of four types of fibre reinforced cement composites. Four composites were conventional steel, polypropylene, glass fibre reinforced mortar, and slurry infiltrated fibre concrete (SIFCON). They concluded that polypropylene fibre reinforced mortar has the best overall durability, while glass fibre reinforced mortar shows the poorest overall performance. Steel fibre reinforced mortar showed noticeable reduction in flexural strength and a dramatic increase in toughness. For SIFCON, the reductions in both strength and toughness were moderate. They also presented a prediction model for the long term deterioration of steel fibre reinforced mortar. The analysis indicated that corrosion can be very critical for thin panel structures of the order of 12.5 mm in depth but diminishes substantially for structures with depth about 100 mm or larger.

Mangat and Motamedi[76] have reported the results of an experimental investigation to determine the influence of steel fibre reinforcement on the creep of cement matrices under compression. Creep tests were carried out at a number of applied stress-strength ratios ranging between 0.3 to 0.9. Melt extract and hooked steel fibres were used at volume fractions ranging between 0 and 3% by volume of a mix. Three types of cement matrices were used namely cement-mask, mortar and two mix proportions of concrete. They concluded that steel fibres restrain the creep of cement matrices at all stress-strength ratios, the restrain being greater at lower stresses and at higher fibre contents. Steel fibres are effective in restraining only the flow component of creep of cement matrices, the delayed elastic component being unaffected.

Girzybowski and Shah[77] have proposed an analytical model which incorporates many parameters and enables progressive cracking development to be predicted in fibre reinforced concrete subjected to reinforced shrinkage. They have concluded that the addition of 0.25% fibres reduces the average crack width to a value which is one third that of specimens without fibres. The ring test proved to be an appropriate test to measure the influence of fibres on cracking of concrete enclosed by restrained shrinkage.

Mawenya[78] reviewed the research work carried so far in the field of sisal fibre reinforced concrete. He reviewed the characteristics of sisal as a reinforcing fibre, manufacture of SFRC, behaviour of SFRC members under tensile and flexural loads and durability of SFRC. Based on the review, he has concluded that sisal fibres have significant mechanical properties that make them eligible as reinforcement for concrete. The sisal fibres impart tensile strength, ductility and toughness to concrete matrix. There is little improvement in the ultimate tensile strength when short fibres (15-75 mm) are used, but the fibres inhibit early cracking and improve ductility. When continuous fibres are used, there is very pronounced strengthening effect.

Fageiri[79] carried out an experimental investigation on the possibility of using kenaf fibres to reinforce rich cement-sand mortar to produce corrugated sheets. He concluded that the tensile properties of kenaf fibres are comparable to those of some natural fibres (sisal) and synthetic fibres(polypropylene) that are used to reinforce a low tensile strength matrix. He also concluded that the addition of these fibres (1.6% by weight) to rich cement-sand mortar (1.5% by weight) to produce corrugated sheets has substantially improved upon the bending moment capacity and impact resistance of similar corrugated plain rich cement-sand sheets, but has slightly increased their water absorption capacity. There is little effect on the density of plain sheets because of fibres.

Saluja et al.[80] carried out study of the compressive strength of steel fibre reinforced concrete. Based on the experimental results, they have suggested a rational method to predict compressive strength of the steel fibre reinforced concrete

Siddique and Venkataramana[81] conducted some preliminary tests to find out the suitability of san fibre.

Panarese, W.C.[82] presented a general discussion on various types of fibres like synthetic fibres, glass fibres and steel fibres etc.

Siddique and Venkataramana[83] have reported the effect of san fibre on the static and impact strength of plain concrete sheets. They concluded that the presence of san fibre enhances the static and impact strength of concrete sheets.

Mwamila[84] has proposed the idea of reinforcing concrete beams with the twines made of sisal fibres.

Robert, C. et al.[85] have discussed the increased ductility afforded by conventionally reinforced concrete sections through the inclusion of deformed steel fibres. Experimental results have been compared with the theoretical approach based on moment curvature relationship. Based on their investigation they concluded that the use of fibres helps to improve the ductility of the section.

Dwarakanath and Nagaraj[86] studied experimentally the deformational behaviour of conventionally reinforced steel fibre concrete beams in pure bending. They conducted the experiments with two groups of the beams. One group of beams has steel fibres dispersed in the entire volume of the beam and the second has fibres dispersed over half the depth of the beam on the tension side. Based on their study they have concluded that the half depth fibre inclusion requiring only half the quantity of fibres of full depth inclusion is found to be equally effective in improving the deformational behaviour of the beams.

CHAPTER - III

DETAILS OF EXPERIMENTAL WORK

3.1 Test Programme

In this chapter, experimental programme (i) to investigate the various properties of the natural San fibre (ii) its effect on the properties of concrete, and (iii) its effect on reinforced concrete have been presented.

The programme was designed in two stages. In the first stage, various physical and mechanical properties of the San fibre were determined. In the second stage, the effect of San fibre on various properties of concrete, when used as reinforcement were investigated.

3.1.1 Test Programme - Stage 1

The following physical and mechanical properties of the San fibre, and their experimental determination are discussed in detail and the values found are presented in chapter 4.

(a) Diameter of the fibre

(b) Water absorption capacity of the fibre

(c) Specific gravity of the fibre

(d) Tensile strength of the fibre in natural dry state as well as in the alkaline medium of NaoH

(e) Dimensional stability of the fibre

3.1.2 Test Programme - Stage 2

In the second stage the following test Programme was planned.

(a) Testing plain concrete and fibre concrete to compare their compressive strength, and modulus of elasticity.

(b) Testing for tensile strength in order to compare the indirect tensile strength (split cylinder) and flexural tensile strength (modulus of rupture) of plain and fibre concrete.

(c) To investigate the flexural behaviour of simply supported fibre reinforced concrete beams.

(d) To investigate the strength of plain and fibre reinforced concrete sheets under static and impact loading.

(e) To investigate the flexural behaviour of simply supported beams reinforced conventionally with steel as well different percentages of fibres.

(f) To study the behaviour of plain concrete beams reinforced with twines, and with fibres as well as twines.

3.2 Materials

Cement, fine aggregate, coarse aggregate, san fibre, water, twines made of san fibres, and conventional steel used throughout the investigation, had the following properties.

(i) Cement

Ordinary portland cement was used. It was tested for its physical properties, the test data are listed in the table 3.1.

All the tests were carried out in accordance with the procedure laid down in IS: 269 - 1967(96).

(ii) Fine Aggregate

Locally available sand was used as fine aggregates. The particle size distribution and other properties are given in table 3.2. Other foreign matter present in the sand were separated before use.

(iii) Coarse Aggregate

Locally available crushed stone aggregate of maximum size 20 mm was used. The properties are listed in table 3.3. Coarse aggregate was sieved through IS 150 micron sieve to remove dirt and other foreign material.

(iv) Water

Water free of harmful amounts of deleterious materials was used for both mixing and curing. Potable water, is generally considered satisfactory for mixing and curing concrete.

(v) Fibres

Natural San fibres were used. Various physical properties of the san fibre have been described and presented in chapter 4. The fibres were cut manually by scissors to an accuracy of ± 2mm. Fibres of five different lengths viz. 15mm, 20mm, 25mm, 30mm and 35mm were used. Six different proportions of fibres (0.25 to 1.5% with an increment of 0.25%) of each length were used.

(vi) Twines

San fibre twines of various diameters were tested for their tensile strength. But only 2.95 mm diameter twines were used in the experiments because twines of this diameter are commercially available. Strength properties of twines are presented in chapter 9.

(vii) Reinforcing Steel

Deformed (ribbed tor) steel bars of 12mm and 8mm nominal diameter were used as main tensile reinforcement and 6 mm diameter for shear stirrups. The salient properties are listed in table 3.4.

(viii) Concrete Mix

Concrete mix having a cube strength of 15 N/mm^2 at 28 days was designed as per ISI Specification. The proportions for the concrete, as determined were 1:1:8:3:6 with a water cement ratio of 0.58 by weight.

3.3 Specimen types and their designation

For the strength tests viz., compressive strength, indirect tensile strength, and modulus of elasticity, the standard 150 x 150 x 150 mm cast iron cube moulds and 150 mm diameter and 300 mm long cast iron cylindrical moulds were used. Steel beam moulds 101.6 x 101.6 mm in cross-section and 508 mm long were used for flexural tensile strength tests.

For sheets, a wooden mould with inner dimension 300 mm x 300 mm x 30 mm was used.

The specimens were classified as A, B1 to B5 . . . G1 to G5 series. The first series i.e. "A" was with out fibres and the remaining thirty series were for six volume fractions of the fibres, each having five fibre lengths. Each series was the average of three specimens.

Each series represents a particular type of specimen e.g. " B1", which represents FRC-15-0.25, stands for specimen cast with fibre concrete containing fibres having fibre length 15mm and volume percentage 0.25%.

In case of conventionally reinforced beams the series were classified as AU, B3U, C3U, D3U for under reinforced beams and AO, B3O, C3O and D3O for over-reinforced beams. Each series was the average of the two specimens. Series "AU" and "AO" represent under - reinforced beams and over - reinforced [illegible] beams without fibres, and the remaining series are reinforced concrete beams with san fibres.

The series for sheets were SA, SB3, SC3, and SD3. Each series was the average of three specimens. Series "SA" was for plain cement concrete sheets and the remaining were for with fibres.

Series AT1, AT2 and AT3 represent concrete beams reinforced with twines of three different percentages (0.7512%, 0.5467%, 0.4100% of the cross-sectional area of the beam),and D3T1, D3T2, and D3T3 stand for the concrete beams reinforced with twines of three different percentages and fibres (lengths 25 mm & 0.75% by volume of concrete).

3.4 Mixing, Compaction and curing

(a) Mixing

Uniform dispersion of fibres throughout the mix has to be ensured during the mixing process. In order to obtain it, the following procedure was adopted.

After all the constituent materials were mixed in the mixer, in the same manner as for plain concrete, about 1/5th of the required water was added to the mix. Small quantities of fibres were released manually and gradually taking care that the fibres were not fed in bunches. After adding about 1/3rd of the quantity of fibres, some more water (about 1/3rd of the remaining quantity) was added to the mixer, and the remaining quantity of fibres was added again slowly and in small quantities. Finally, the remaining water was added and the mixer was run till good homogeneous mix, as visually observed, was obtained. If any lumping or balling was found at any stage, it was taken out, loosened and again added manually.

(b) Compaction

For compacting fibre reinforced concrete usual methods of mechanical vibration such as obtained in a needle or table vibrator, can be used. Needle vibration however, is not preferred with higher volume content of fibres, as the holes left by the needle may remain unfilled due to interlocking effect of the fibres. Table vibrator is the most suitable as it gives the advantage of fibres acquiring a tendency to align themselves in a plane perpendicular to the direction of vibration. This results in random planner orientation. A fibre mix generally requires somewhat greater vibration to move the mix and consolidate it into the moulds. The compaction of the specimens was done on a platform vibrating table with a speed range of 12000 ±400 rpm and an amplitude of 0.055 mm.

(c) Curing

Identification marks were etched into the specimens after 1.0 hour of casting, and they were allowed to set in the moulds for

24 hours after which they were taken out of the moulds and immersed in fresh water for curing for a specified period of time. The specimens were then removed from water and stored in a room till their time of testing.

3.5 Instrumentation

(a) Deformator

Surface strains in the concrete beams were measured by a demountable mechanical strain gauge (Whittemore Deformator) with a gauge length of 152.4mm and least count of 0.00254mm. The readings were taken on the deformator by inserting the gauge points in the punch marks on the small brass studs (gauge points) fixed on the beam surface.

(b) Gauge Points

The gauge points consisted of brass studs, 9.0mm diameter with punch marks in the centre and fixed to the beam surface with araldite. The spacing of the gauge points(brass studs) was kept 25.4 mm in the transverse direction(Vertically). The location of the gauge points is shown in the fig.3.2.

(c) Steel Studs

Steel studs of 15mm diameter and 18mm long with suitable fine drilled holes(for inserting the gauge points of the Whittemore

Deformator) were welded to one of the reinforcing bars as shown in fig.3.3(a) and fig.3.3(d).

The strains of the steel bars while under loading could thus be recorded by measuring the deformations between the gauge points of the steel studs. The free ends of these steel studs just touched the inside surface of the steel moulds.

(d) Dial gauges

Dial gauges with magnetic base were used to measure the deflections. The least count of these gauges was 0.002mm.

3.6 Testing Procedure

3.6.1 Compressive Strength

Compression tests were made in accordance with ISI specifications with a loading rate of 140 kg/cm^2/minute on 250 ton compression testing machine. Plate 3.1 and 3.2 show the cube of plain concrete and fibre concrete under test for compressive strength.

The cubes of 150 mm X 150 mm X 150 mm were tested in direct compression on a compression testing machine. The specimens were placed in the machine such that the load is applied on any pair of faces other than the one having the marking. Then the load was gradually applied on the specimen till the specimen developed a crack. This was automatically exhibited by the machine. The ultimate load divided by the area of cross-section of the specimen gives the compressive strength.

3.6.2 Modulus of Elasticity

These tests were carried out in accordance with ISI specifications. Three 150 mm cubes and three 150 mm X 300 mm cylinders were tested from each series. Plate 3.3 shows fibre concrete cylinder under test for modulus of elasticity.

The testing was done at the age of 28 days. The tests were performed on a 250 ton compression testing machine. The secant modulus was calculated at 33% of the maximum cube strength and is the average of 3 samples.

3.6.3 Indirect Tensile Strength

These tests were carried out on cylindrical specimens of 150 mm X 300 mm size. To determine the tensile strength, the specimens were placed between two platens of the compression testing machine. The loading edge was kept parallel to the longitudinal axis of the cylinder. Plate 3.4 and 3.5 show plain concrete and fibre concrete cylinders under test for split tensile strength.

The compressive load was gradually applied on the specimen till the specimen failed along the vertical diameter. The ultimate load at which failure occurred was automatically indicated by the machine. Thus ultimate load at which the specimen failed, was noted. The split tensile strength was calculated by using following expression

$$\frac{2\ P}{\pi\ D\ L}$$

Where

P is load in Newton at failure

D is diameter of the specimen in mm

L is length of the specimen in mm

3.6.4 Flexural Tensile Strength

The flexural tensile strength properties were studied using specimens 101.6 X 101.6 X 500.0 mm. Each test result was the average of three specimens. Specimens were tested on a 50 ton universal Testing Machine. Plate 3.6 shows fibre concrete beam under test for flexural tensile strength.

The loads and corresponding deflections were observed for every 1000 N interval for increasing loads until failure. It was observed that, while the load was increasing the deflection gradually increased. The dial gauge recorded a sudden increase within a fraction of a second of failure.

The flexural tensile strength (modulus of rupture) of the specimens expressed as modulus of rupture, was calculated by using following formula

$$\frac{PL}{bh^2}$$

Where

P is load in Newton at failure

L is length of the beam in mm

b is width of the beam in mm

h is depth of the beam in mm

3.6.5 Sheet Testing

Two types of tests were carried out on the plain and fibre reinforced concrete sheets.

(a) Static Test

(b) Impact Test

In both the tests , the sheets were supported on two parallel edges with other two edges remaining free.

For static test, plain and fibre reinforced cement concrete sheets were subjected to static loading in a universal testing machine. The load was applied at the centre with an increment of 200 N and the central deflection was observed.

Impact strength test was carried out by a falling weight method, which was used to determine the impact resistance of the plain and fibre reinforced cement concrete sheets. In this test a metallic piece of weight 69 N was allowed to fall freely on the sheets so that the impact is at the centre of the sheets. The impact strength was taken to be proportional to the height from which the weight has to be allowed to fall to fracture the sheets. Impact strength set up has been shown in fig.3.1.

3.6.6 Testing of Conventionally Reinforced Fibre Concrete Beams

Under-reinforced and over-reinforced concrete beams were cast with san fibres of optimum length, 25mm and with three percentages of fibres by volume ie; 0.25%, 0.50% and 0.75%.

The beams were tested on a 50 ton universal testing machine. The effective span of the beams between the supports was kept at 1080mm. The initial readings of the dial gauges, surface studs(brass Studs) and steel studs were recorded at the start of the experiment. The load was applied at a uniform rate. The load was held constant during each set of readings for strains in concrete and steel and, deflections.

The control cubes of the corresponding beam were also tested on the same day. The average values of compressive strengths are listed in column 6 of the tables 3.5 and 3.6.

3.6.7 Testing of Beams Reinforced With Twines

To study the effect of the twines (twines made of only one diameter ie; 2.95 mm was used because it is commercially available) made of san fibres, a total of 6 series of concrete beams(100mm x 100mm x 500mm) were cast. Out of these, 3 series were cast with three different percentages of twines (0.7512%, 0.5467% and 0.4100% of the cross-sectional area of the beam) and the remaining 3 series of the beams were cast with three percentages of twines along with the optimum percentage of the fibres i.e. 0.75%.

The anchoragement for the twines was provided with the help of small wooden blocks of size 10mm x 10mm x 90mm. Circular holes of 3.0 mm diameter were made so that twines may pass through them and then can be tied. The arrangement of placing the twines of all the three percentages are shown in fig.3.4. All the beams were tested on a 50 ton universal testing machine. The deflections were recorded for every 1000 N interval for increasing loads until ultimate failure.

Table 3.1

Properties of Cement

S.No.	Characteristics	Value Obtained Experimentally	Value specified by IS:269-1967(96)
1.	Fineness - determined by sieving the cement through standard IS-90 micron seine	9.5%	$>$ 10%
2.	Normal consistency, weight of water percent weight of cement	28%	--
3.	Setting time in minutes (i) Initial (ii) Final	40 300	$\nless$ 30 $\ngtr$ 600
4.	Compressive strength in in N/mm^2 of 1 : 3 cement sand mortar (i) at 3 days (ii) at 7 days	17.8 24.2	$\nless$ 16.0 $\nless$ 22.0
5.	Specific gravity	3.125	--

Table 3.2

Sieve Analysis and Physical Properties of Fine Aggregate

IS Sieve	wt. retained in gms per hundred gms of sample	% retained	Cumulative % retained
4.75 mm	4	0.4	0.4
2.36 mm	98	9.8	10.2
1.18 m	139	13.9	24.1
600 micron	207	20.7	44.8
300 micro	259	25.9	70.7
150 micro	291	29.1	99.8

Fineness modulus = 2.50

Specific gravity = 2.61

Density (loose) N/m^3 = 15310

Density (compacted) N/m^3 = 15950

Table 3.3

Sieve Analysis and Physical Properties of Coarse Aggregate

IS Sieve	wt. retained in gms per hundred gms of sample	% retained	Cumulative % retained
80 mm	--	--	--
40 mm	--	--	--
20 mm	2.130	2.130	2.13
10 mm	81.500	81.500	83.63
4.75 mm	10.750	10.750	94.38
2.36 mm	3.000	3.000	97.38
1.18 mm	0.900	0.900	98.28
600 micron	0.600	0.600	98.88
300 micron	0.400	0.400	99.28
175 micron	0.200	0.200	99.48

Fineness modulus = 6.73

Specific gravity = 2.69

Density (loose) N/m^3 = 15370

Density (compacted) N/m^3 = 16320

Table 3.4

Physical Properties of Flexural and Shear Steel

S.N.	Diameter of bar in mm	Yield Stress N/mm^2	Ultimate Strength N/mm^2	Yield Strain	% Elongation	Young's Modulus N/mm^2
(1)	(2)	(3)	(4)	(5)	(6)	(7)
1	Deformed bar 12mm	671.6	723.0	0.00231	17.24	2.32×10^5
2	Deformed bar 8mm	490.0	561.0	0.00212	18.39	2.29×10^5
3	Plain bar 6mm	409.3	561.1	0.00265	23.60	2.69×10^5

Table 3.5

Physical Data of Under-Reinforced Beams

Width of the beam = 101.6 mm

Depth of the beam = 152.4mm

Effective depth of the beam = 131.4mm

Area of steel = 100.6 mm^2(2 Number, 8mm dia deformed bars)

% of steel reinforcement = 0.7422% of cross-sectional area of the beam

Yield Stress of steel reinforcement = 490.0 N/mm^2

Ultimate Stress of steel reinforcement = 561.0 N/mm^2

Shear Steel = Two legged vertical stirrups, 6 mm dia plain steel at 80 mm c/c (Only in shear span)

S.N. (1)	Beam Series (2)	Beam Type (3)	Fibre Volume % of Concrete (4)	Length of Fibres in mm (5)	Average Control Cube Strength in N/mm^2 (6)
1	AU	Reinforced	--	-	15.212
2	B3U	RFC-25-0.75	0.75	25	15.916
3	C3U	RFC-25-0.50	0.50	25	15.476
4	D3U	RFC-25-0.25	0.25	25	15.165

RFC stands for reinforced fibre concrete

Table 3.6

Physical Data of Over-Reinforced Beams

Width of the beam = 101.6 mm

Depth of the beam = 152.4mm

Effective depth of the beam = 131.4mm

Area of steel = 226.2 mm^2(2 Number, 12 mm dia deformed bars)

% of steel reinforcement = 1.6943% of cross sectional area of the beam

Yield Stress of steel reinforcement = 671.6 N/mm^2

Ultimate Stress of steel reinforcement = 723.0 N/mm^2

Shear Steel = Two legged vertical stirrups, 6 mm dia plain steel at 80 mm c/c (Only in shear span)

S.N.	Beam Series	Beam Type	Fibre Volume % of Concrete	Length of Fibres in mm	Average Control Cube Strength in N/mm^2
(1)	(2)	(3)	(4)	(5)	(6)
1	A0	Reinforced	-	-	15.212
2	B30	RFC-25-0.75	0.75	25	15.916
3	C30	RFC-25-0.50	0.50	25	15.476
4	D30	RFC-25-0.25	0.25	25	15.165

RFC stands for reinforced fibre concrete

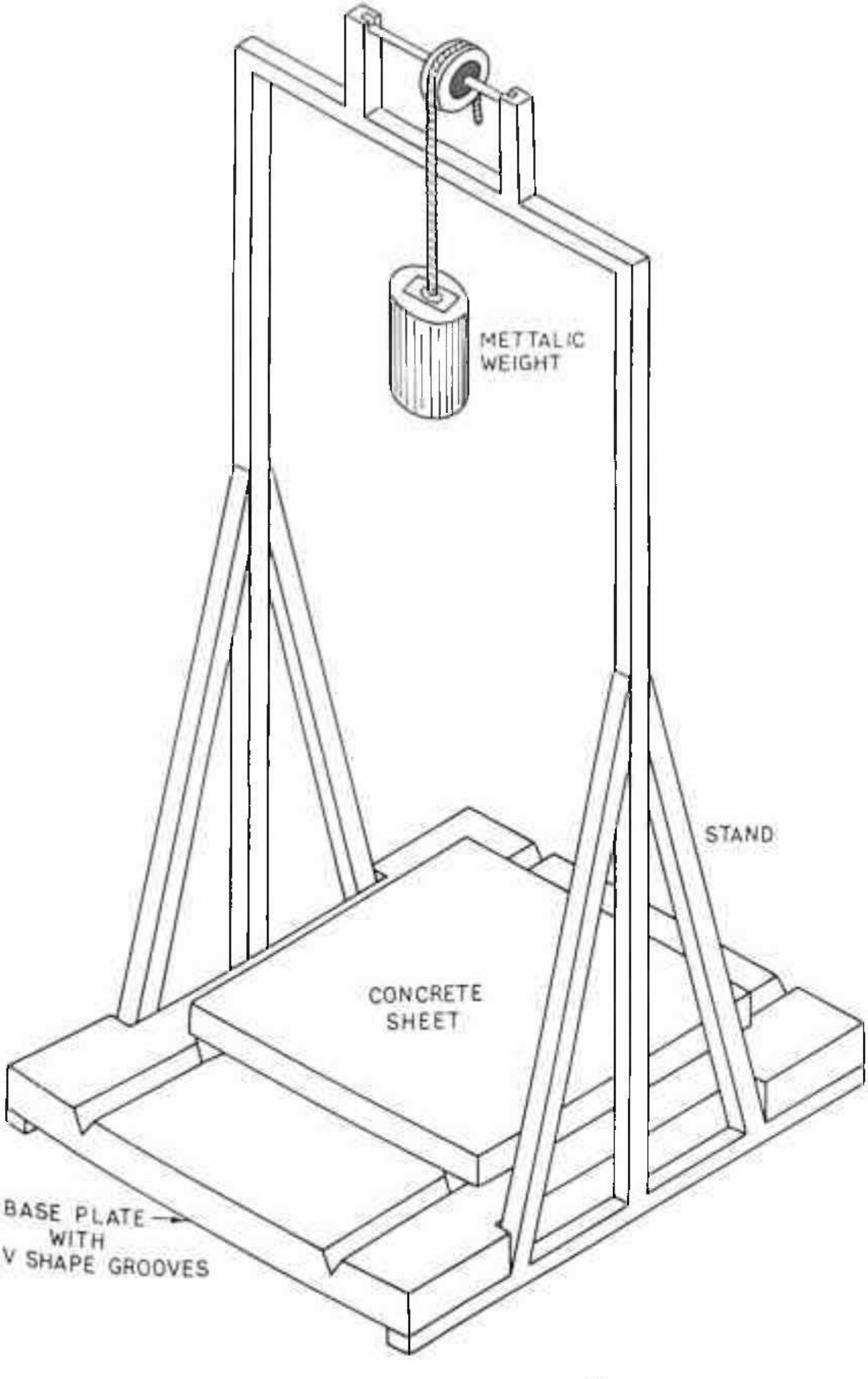


FIG.3.1 IMPACT STRENGTH TEST SET UP

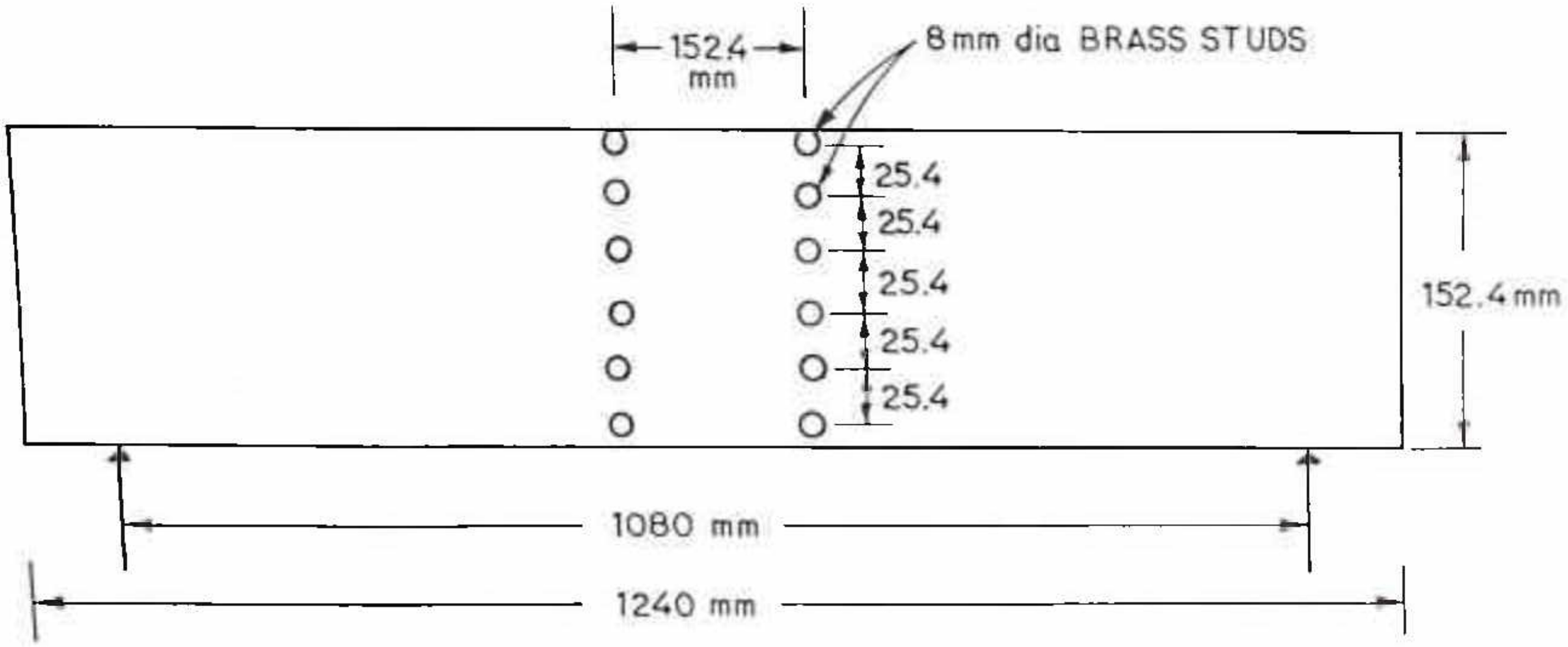
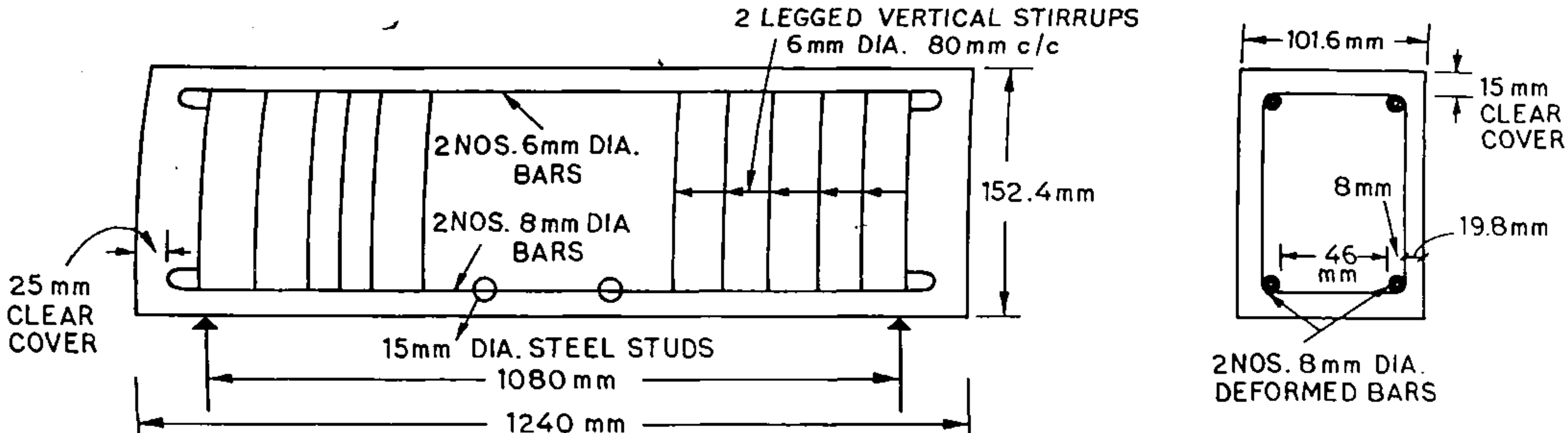
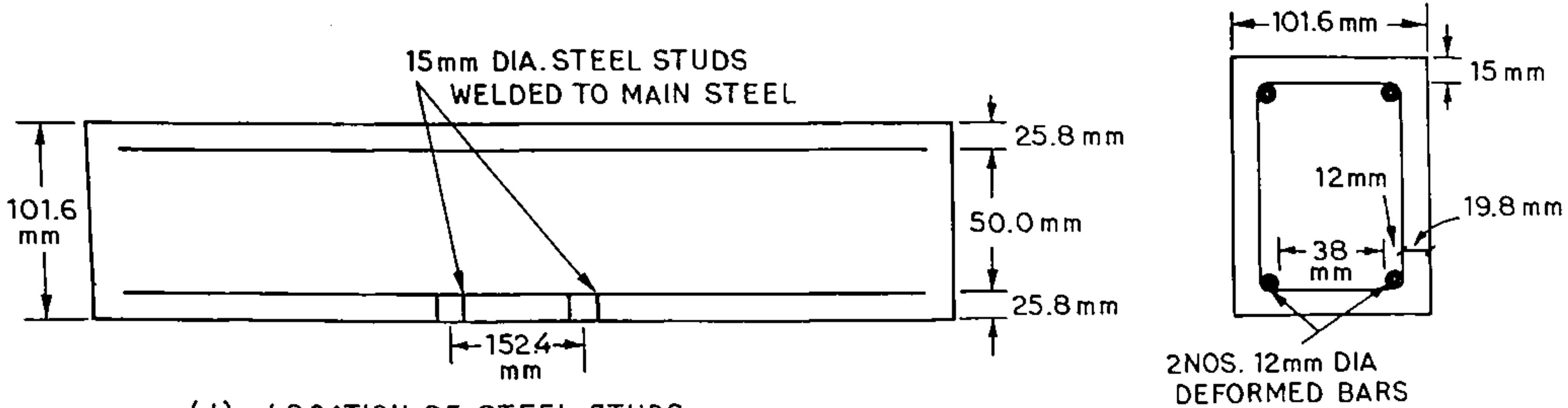


FIG.3.2 LOCATION OF GAUGE POINTS (BRASS STUDS) FOR FLEXURAL CHARACTERISTICS.



(a) LONGITUDNAL SECTION OF BEAM

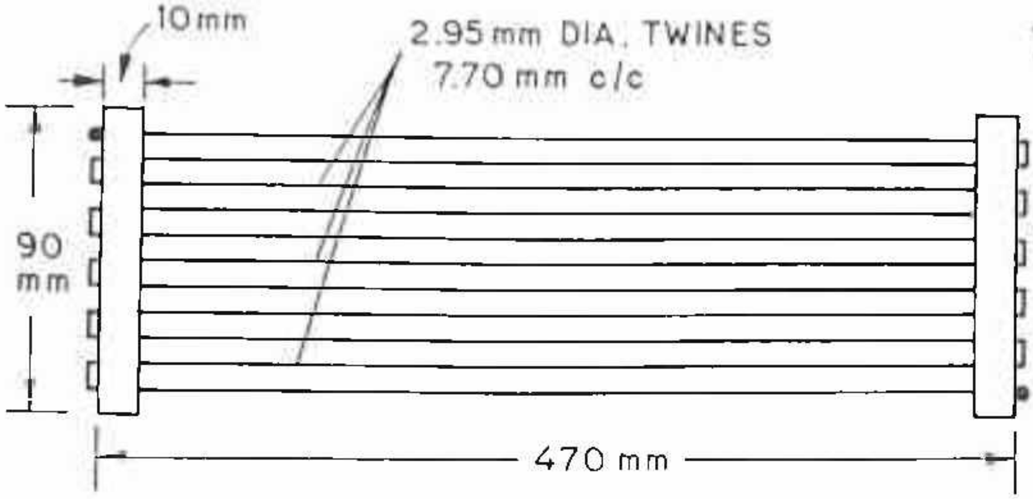
(b) CROSS-SECTION OF UNDER REINFORCED BEAMS



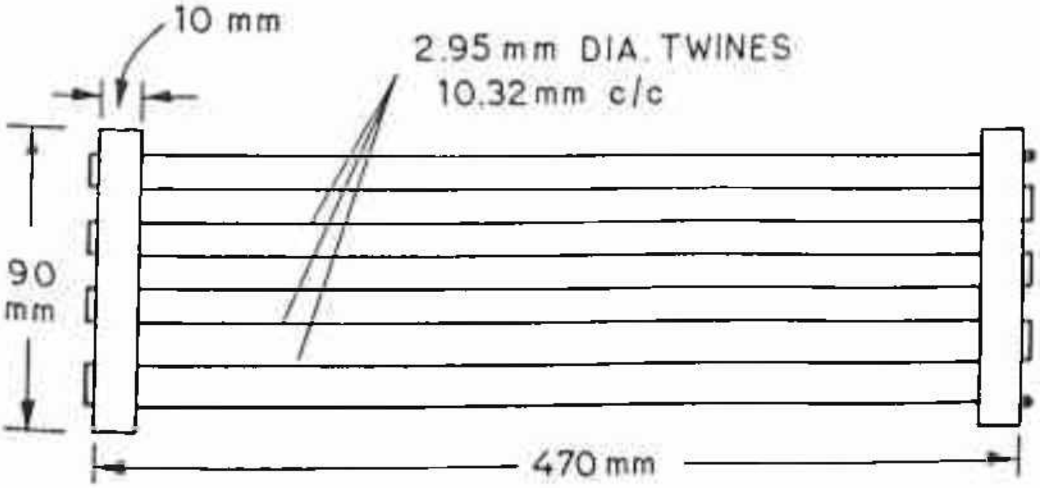
(d) LOCATION OF STEEL STUDS

(c) CROSS-SECTION OF OVER REINFORCED BEAM

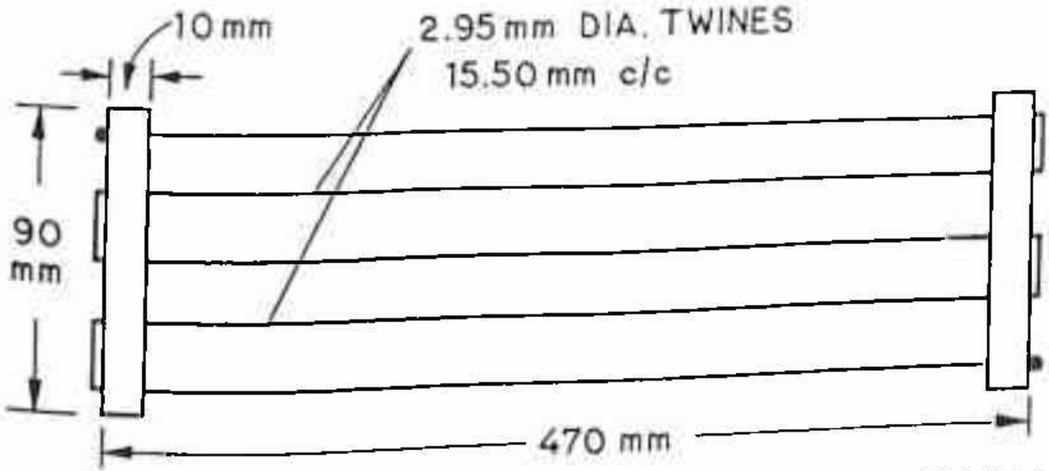
FIG.3.3 DETAILS OF TEST BEAMS FOR FLEXURAL CHARACTERISTICS.



(a) TWINES, 0.7512 % OF THE CROSS-SECTIONAL AREA OF THE BEAM.



(b) TWINES, 0.5467 % OF THE CROSS-SECTIONAL AREA OF THE BEAM.



(c). TWINES, 0.4100 % OF THE CROSS-SECTIONAL AREA OF THE BEAM.

FIG.3.4 PLAN SHOWING ARRANGEMENT FOR PLACEMENT OF TWINES.

PLATE 3.1 PLAIN CONCRETE CUBE UNDER TEST FOR COMPRESSIVE STRENGTH.

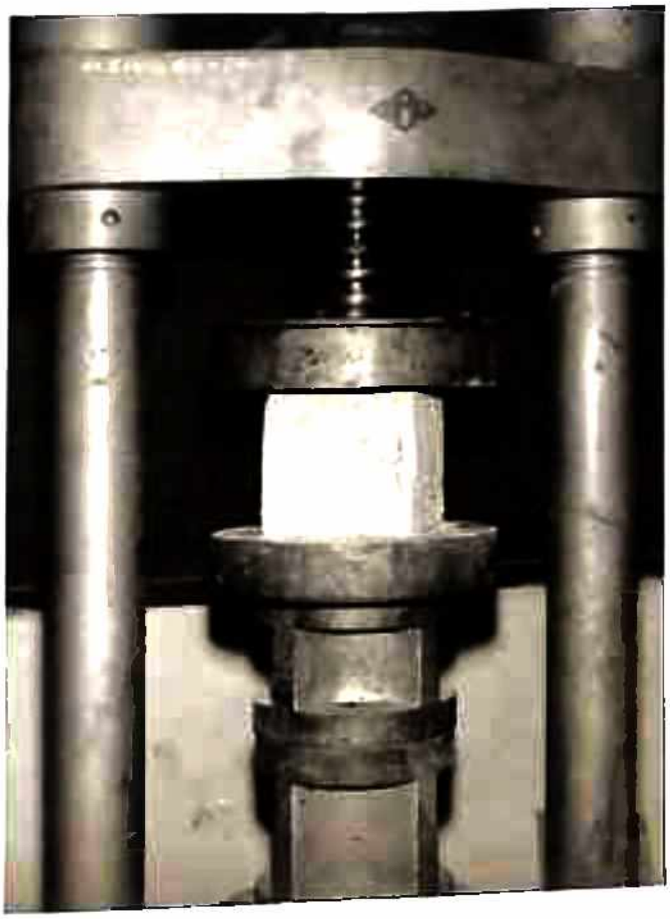


PLATE 3.2 SAN FIBRE REINFORCED CONCRETE CUBE UNDER TEST FOR COMPRESSIVE STRENGTH.

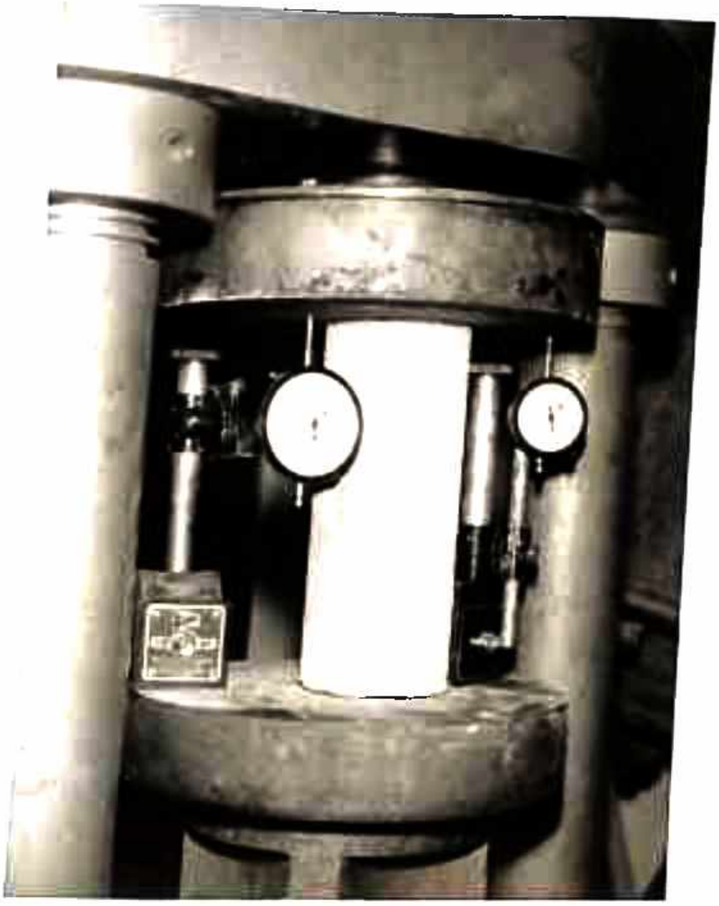


PLATE 3.3 SAN FIBRE REINFORCED CONCRETE CYLINDER UNDER TEST FOR MODULUS OF ELASTICITY.

PLATE 3.4 PLAIN CONCRETE CYLINDER UNDER TEST FOR SPLIT TENSILE STRENGTH.

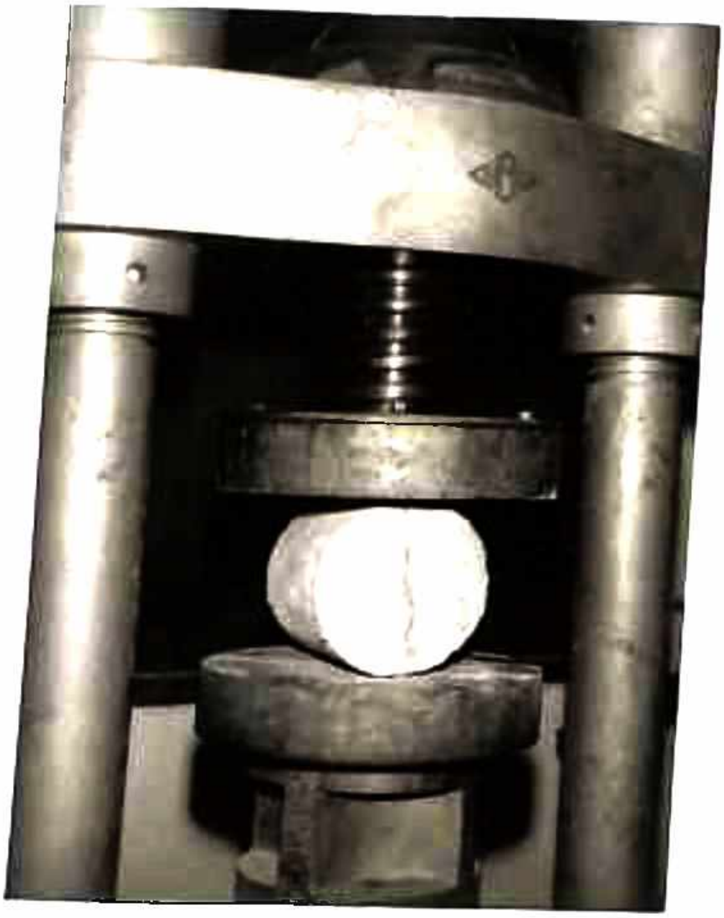


PLATE 3.5 SAN FIBRE REINFORCED CONCRETE CYLINDER UNDER TEST FOR SPLIT TENSILE STRENGTH.

PLATE 3.6 SAN FIBRE REINFORCED CONCRETE BEAM UNDER TEST FOR FLEXURAL TENSILE STRENGTH.

CHAPTER - IV

PHYSICAL AND MECHANICAL PROPERTIES OF SAN FIBRE

In this chapter some physical and mechanical properties of natural san fibre such as diameter, water absorption capacity, specific gravity, tensile strength characteristics, and its dimensional stability have been presented.

4.1 Description of the Fibre

San fibre is extracted from the San plant which grows to about 1.0 to 2.5 m in height and is light green in colour. The diameter of the plant varies from 10 to 30 mm. The stem of the plant is fully covered with a thin layer of fibrous skin, which can be removed from the stem in longitudinal pieces of good length, even at the green stage but with difficulty. To make extraction of the fibres easy, the uprooted plants are placed under water for a period of 3 to 4 weeks, after which they are taken out of the water and the fibrous skin is separated easily. The fibres by this time are found to have acquired light yellowish colour.

4.2 Diameter of the Fibre

It is very difficult to identify a single fibre of the smallest diameter or cross-section. An apparently visible single fibre can be further split into many minute fibres of smaller diameter or cross-section. As such sufficient care must be taken to ensure that the sample selected for measurement of the diameter was that of a single fibre. In the present work, diameter of the San fibre was measured by an oculumeter. Observations for the cross-section of the fibres were made at three different locations along the length for each fibre of several samples. Measurements were taken at both the ends and at the centre of the sample.

Table 4.1 shows typical values of the diameter of San fibre. Diameter of the other natural fibres reported by other authors are given in the table 4.2.

As it is clear from the tables 4.1 and 4.2, the diameter of san fibre is more or less same as the diameter of sisal and jute fibre but is smaller in size than that of all other natural fibres.

4.3 Water Absorption Capacity of the Fibre

Water absorption capacity is an important property, which . is necessary to determine for all natural fibres of interest. Results reported in the literature on the water absorption capacity of some natural fibres are given in the table 4.3.

To find out the water absorption capacity of San fibre, several samples of dried fibres were cut in lengths of 60 to 75 mm. These pieces were weighed and placed in water for a specified period of time. Water absorption of San fibre at different time - intervals are tabulated in table 4.4.

It is clear from the table that the rate of water absorption is rapid during first 5 minutes and the fibre almost gets saturated in one day. It can be seen that a fibre absorbs weight of water equal to its own weight.

The inherent capacity of natural fibres to absorb water may lead to a reduction in the effective water-cement ratio of a concrete mix containing natural fibres. For example, an addition of 0.75% of San fibre by volume in fresh concrete mix, with a moisture absorption of 96% for this fibre, a normal water-cement ratio of 0.580 reduces to 0.558.

To overcome this difficulty extra amount of water equal to its absorption capacity is to be added to the concrete mix while mixing.

4.4 Specific Gravity of the Fibre

Specific gravity of fibres like Akwara[42], Lechugullla and Maguey[48], Jute and Coir[68], and Sisal[78] reported in the literature are presented in Table 4.5.

Specific gravity of San fibre was determined by the specific gravity bottle method, using the following formula

$$\text{Sp. gr.} = \frac{W_3 - W_1}{(W_2 - W_1) - (W_4 - W_3)}$$

Where

W_1 = Weight of the flask

W_2 = Weight of flask + water

W_3 = Weight of flask + Dry fibres

W_4 = Weight of flask + fibres + Water

Several samples of San fibre were taken for specific gravity measurements.

One set of measurements given below as a sample, yields

W_1 = 450.5g

W_2 = 980.6g

W_3 = 471.2g

W_4 = 981.2g

a value of 1.029 for the specific gravity of San fibre. The value is comparable with those for jute, akwara etc.

4.5 Tensile Strength of the Fibre

Many researchers have reported the tensile strength of the various natural fibres. Table 4.6 shows the tensile strength, % elongation at break, and modulus of elasticity of various types of natural fibres. Fig.4.1 shows the stress-strain relationship of some natural fibres.

Various samples of San fibre were tested in natural dry state and in an alkaline medium of sodium hydroxide solution of pH value 11.

Representative samples of San fibre were taken out and were cut into lengths of about 100 mm to 120 mm. These were held individually between the jaws of the machine, as shown in plate 4.1. The tensile load was applied gradually until failure.

4.5.1 Tensile Strength In Natural Dry State

40-45 samples of San fibre were tested for their tensile strength in their natural dry state. Results of 10 representative samples are presented in table 4.7.

The average tensile strength of the San fibres in natural dry state was found to be 222.00 N/mm^2. The percent elongation is 1.25 to 1.34 and initial tangent modulus is 2.2 X 10^4 N/mm^2. Fig.4.2 shows the tensile stress strain curve of san fibre in natural dry state.

4.5.2 Tensile Strength In Alkaline Medium

Tensile strength of the san fibres was determined in alkaline medium of Sodium Hydroxide solution of pH 11 after 7, 14 and 28 days. Fibres taken out of the broken concrete specimens were also tested for their tensile strength.

Values of the ultimate breaking strength, expressed in N/mm^2, and with the diameter of the fibre taken in its natural dry state as the reference diameter, are given in table 4.8, and the variation of tensile strength of san fibre with time of immersion in alkaline medium has been plotted in fig.4.3. The elongations at breaking point were also calculated and these results are presented in the table 4.9. It is seen that San fibre shows loss of strength of the order of 14.65%, 20.64% and 30.11% after being kept in alkaline medium for 7, 14 and 28 days respectively. Fig.4.4 shows the stress-strain curves of san fibre in alkaline medium.

The fibres embedded in concrete specimen (which has been air cured after 28 days of usual curing) for over 3-4 months show that there is almost no loss of strength. This could be expected since, concrete, which, though alkaline, would not be a fluid medium and, hence the reduction in strength while in concrete should not be any worse than the order indicated for sodium hydroxide liquid medium. In fact, it would be much smaller.

The elongation results indicate that san fibre has low values of elongation at failure (of the order of 1.30%) when tested in natural dry state and the elongation decreases as the period for which the fibres are kept in alkaline medium increases. This can be seen from the figures in table 4.9.

4.6 Dimensional Stability of the Fibre

Dimensional stability of natural fibres has been investigated by many researchers.[42,43] Uzomaka[42] investigated this by simple immersion drying cycle tests for periods upto 240 hours. Lewis.G.[43] carried out tests for dimensional stability of the fibres when exposed to moisture.

In the present work, dimensional stability of the San fibres were investigated in the same manner as done by Lewis.[43]

Various samples of fibres were taken and were dried at 100°C for 6 hours to constant weight. Measurements for diameters of the fibres were made, and are shown in column 2 of table 4.10. Fibres were placed again in water for 6 hours, dried and their diameters were measured. Values are listed in column 3 of table 4.10. Column 4 Of table 4.10 shows the percentage variation in two measurements. The percentage variation is below 10%, which indicates that there is no appreciable change in the diameter of the fibres in wet and dry conditions.

Table 4.1

Typical Values of Diameters of San Fibre Samples

Sample No.	Diameter at One End in mm	Diameter at Centre in mm	Diameter at Other End in mm
1	0.05	0.06	0.06
2	0.08	0.08	0.07
3	0.04	0.05	0.05
4	0.06	0.07	0.06
5	0.07	0.06	0.08
6	0.08	0.08	0.08
7	0.06	0.06	0.05
8	0.06	0.08	0.07
9	0.03	0.04	0.05
10	0.08	0.07	0.08
Average	0.0610	0.0660	0.0650
Standard Deviation	0.0172	0.0150	0.0126

Table 4.2

Typical Values of the Diameters of Natural Fibres

Fibres	Diameter in mm
Lechuguilla	0.30
Maguey	0.35
Water reed	1.10
Elephant grass	0.45
Plantain	0.43
Musamba	0.82
Jute	0.10
Akwara	1.0 to 4.0
Sisal	0.02 to 0.08
Coir	0.20

Table 4.3

Water Absorption Capacity of Natural Fibres

Fibres	Absorption, percent weight of dry fibres
Lechuguilla	90-105
Maguey	65-70
Coir	110
Jute	120
Bamboo	145-160

Table 4.4

Water Absorption Properties of San Fibre

Wetting time in min	Weight of dry fibres in grams	weight of wet fibres in grams	weight of water absorbed in grams	Absorption, percent weight of dry fibres
5	10.6	18.8	8.2	77.35
10	9.6	18.1	8.5	88.54
30	10.4	20.0	9.6	92.30
60	9.9	19.3	9.4	94.44
180	10.2	19.8	9.6	94.11
1440 (1 Day)	10.8	21.2	10.4	96.29

Table 4.5

Specific Gravity of Natural Fibres

Fibres	Specific gravity
Lechuguilla	1.36
Maguey	1.24
Akwara	0.99
Jute	1.02 to 1.04
Coir	1.12 to 1.15
Sisal	1.205

Table 4.6

Strength Properties of Natural Fibres

Fibres	Tensile Strength N/mm^2	Elongation at break %	Modulus of Elasticity N/mm^2
Elephant grass	178.0	3.60	4936
Water reed	70.0	1.19	5193
Plantain	92.0	5.90	1436
Musamba	83.0	9.70	941
Maguey	390.0	0.50	-
Lechgulila	390.0	0.50	-
Kenaf	295.0	-	22000
Jute	227.0	1.30	30000
Coir	180.0	26.50	-
Sisal	330.0	3.20	26000

Table 4.7

Tensile Strength of San Fibre in Natural Dry State

Sample No.	Diameter of fibre in mm	Breaking load in N	Tensile Strength in N/mm^2
1	0.16	4.26	210.0
2	0.13	3.10	230.0
3	0.14	3.45	225.0
4	0.15	3.45	195.0
5	0.11	2.30	240.0
6	0.12	2.65	231.0
7	0.13	3.00	224.0
8	0.12	2.45	217.0
9	0.16	3.85	190.0
10	0.10	1.90	245.0

Table 4.8

Tensile Strength of San Fibre in Alkaline Medium

State in which Tested	Tensile Strength N/mm^2	% Reduction In strength
1 Dry State	221.96	-
2 7 days immersion in alkaline medium	189.44	14.65
3 14 days immersion in alkaline medium	176.54	20.64
4 28 days immersion in alkaline medium	158.32	30.11
5 Fibre taken out of broken concrete specimen	219.59	1.02

Table 4.9

Tensile Elongation of San Fibre in Alkaline Medium

State in which tested	Elongation mm	% Elongation	% reduction in elongation
1. Natural dry state	0.481	1.30	-
2. Immersed in alkaline medium for 7 days	0.450	1.21	0.09
3. Immersed in alkaline medium for 14 days	0.430	1.16	0.14
4. Immersed in alkaline medium for 28 days	0.390	1.05	0.25
5. Fibres taken out of broken concrete specimens	0.479	1.29	0.01

Table 4.10

Dimensional Stability of San Fibre

Sample No.	Diameter of the fibres dried at 100°C for 6 hours, mm	Diameter of the fibres after keeping in water and again drying mm	Percentage variation
(1)	(2)	(3)	(4)
1	0.050	0.048	- 4.0
2	0.060	0.063	+ 5.0
3	0.070	0.066	- 5.7
4	0.080	0.080	-
5	0.050	0.046	- 8.0
6	0.065	0.070	+ 7.6
7	0.037	0.040	+ 8.1
8	0.060	0.060	-
9	0.050	0.045	- 10.0
10	0.070	0.070	-

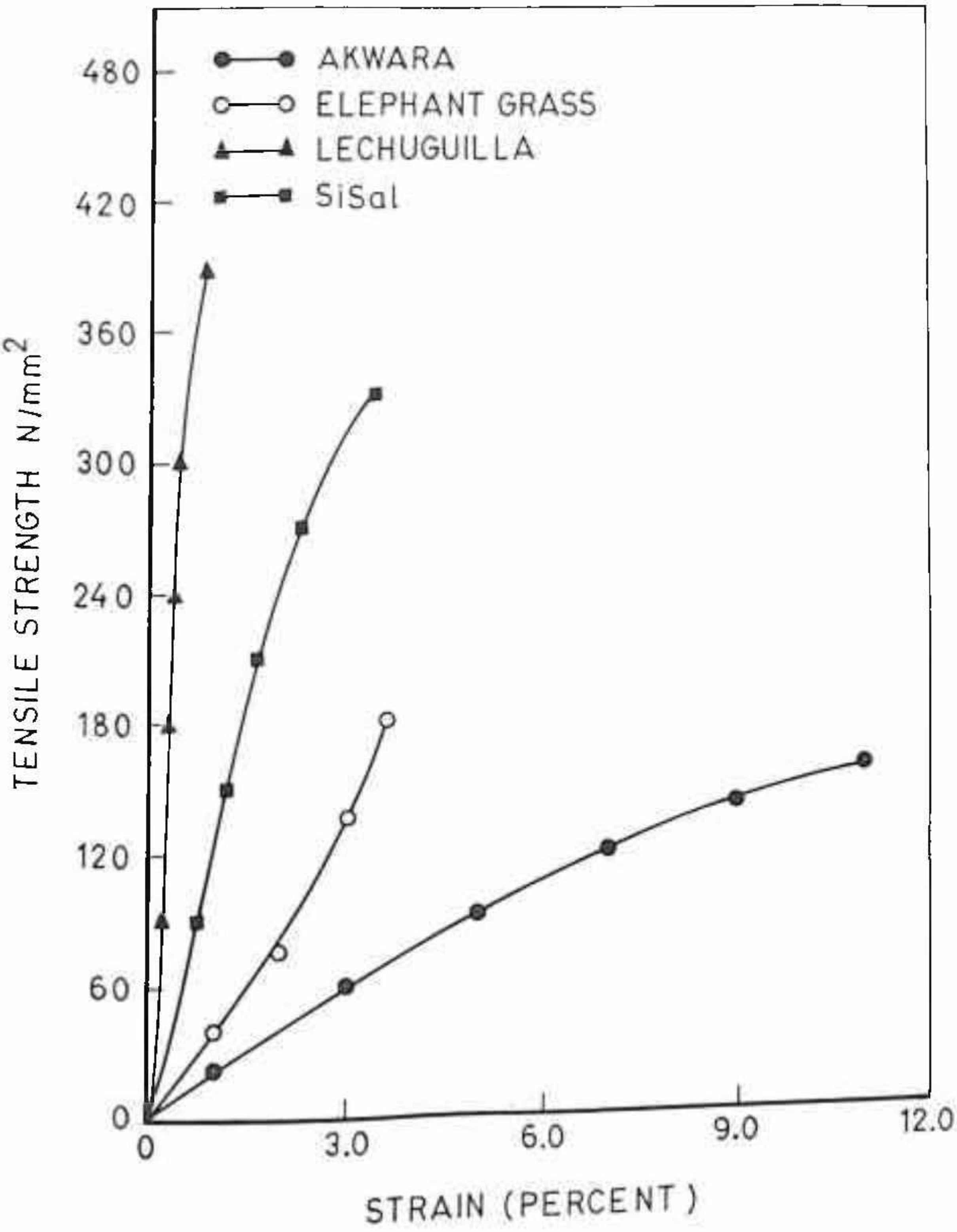


FIG. 4.1 STRESS-STRAIN CURVE OF SOME NATURAL FIBRES

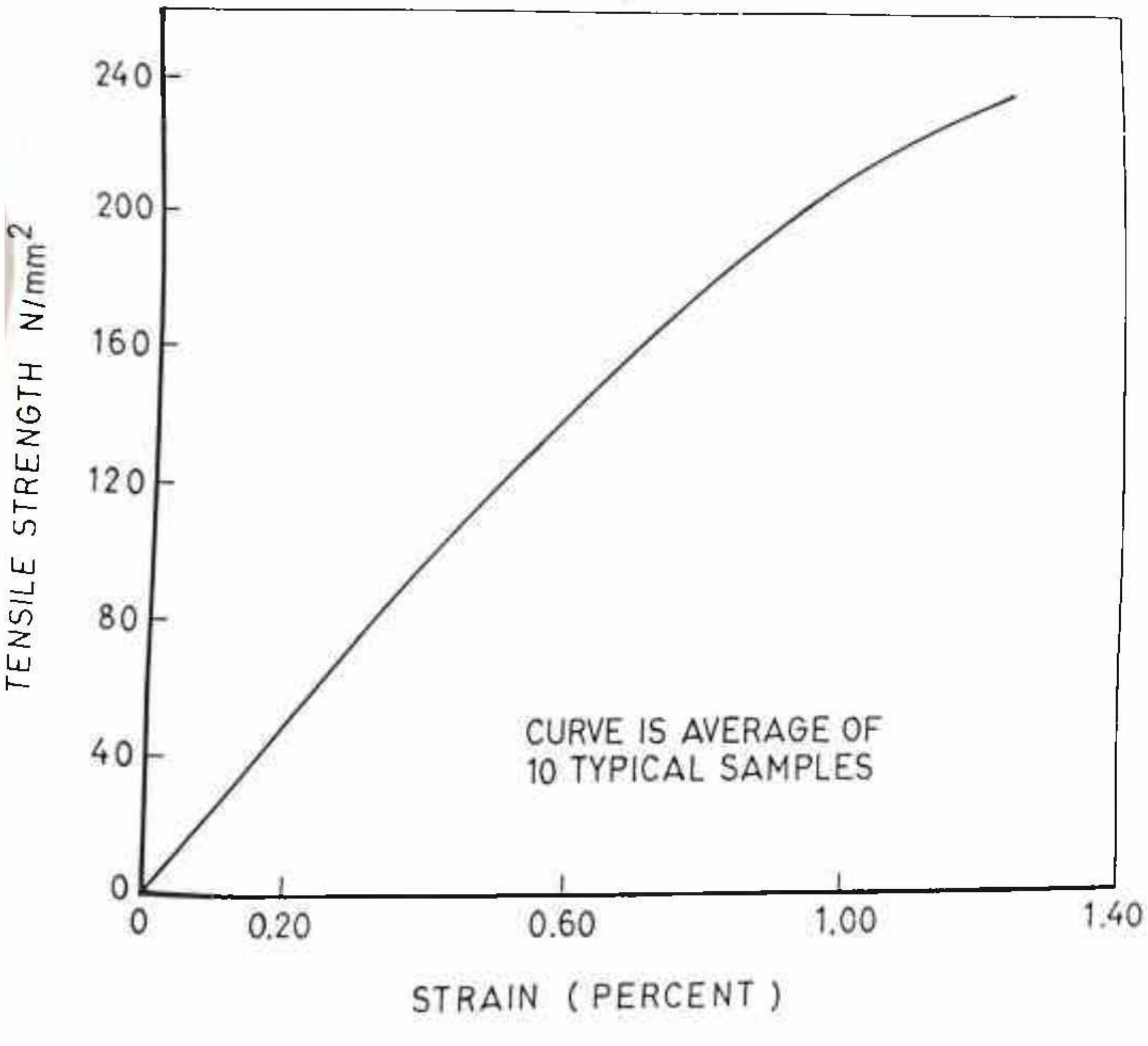


FIG. 4.2 STRESS-STRAIN CURVE OF SAN FIBRE IN NATURAL DRY STATE

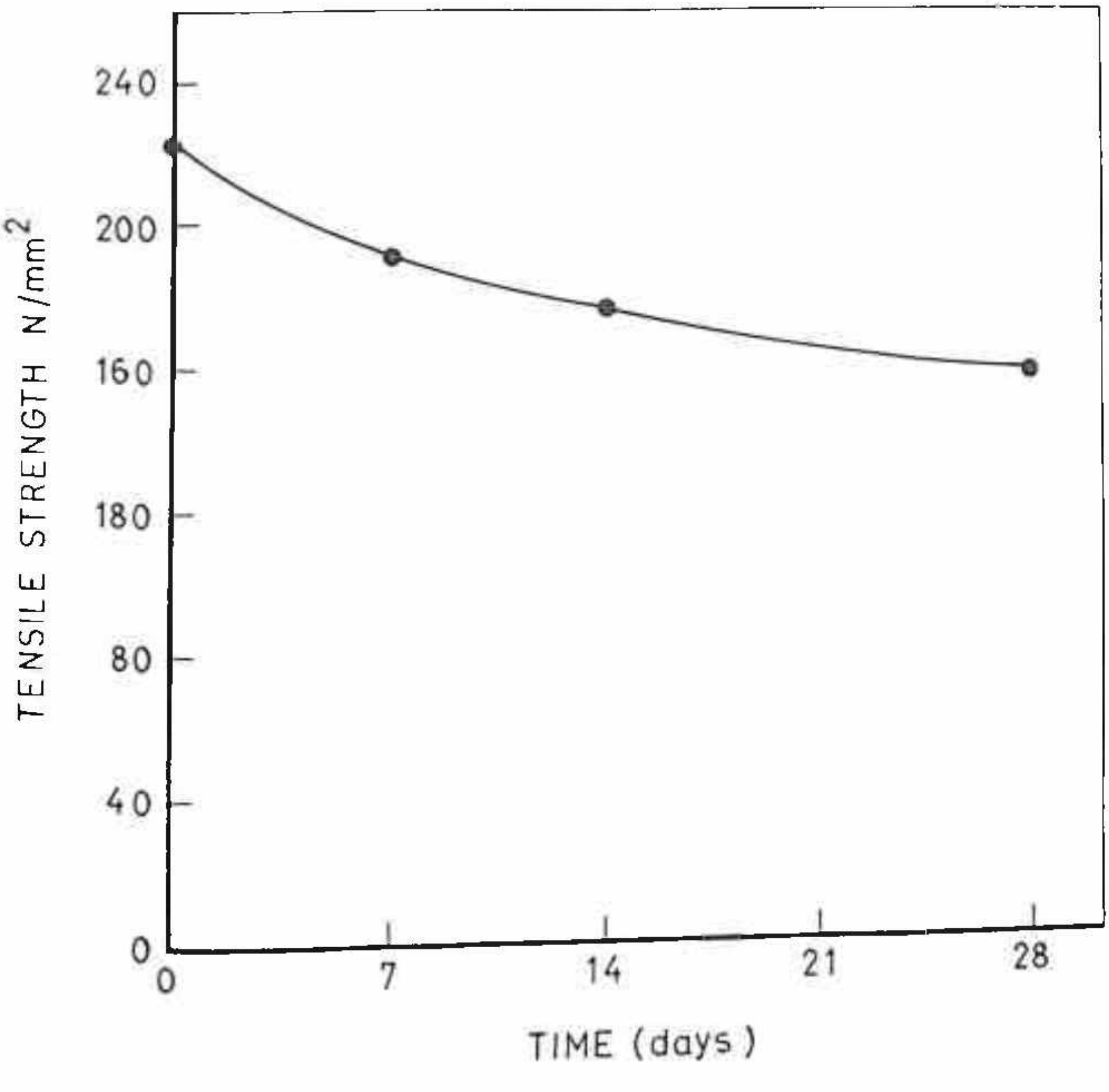


FIG.4.3 VARIATION OF TENSILE STRENGTH OF SAN FIBRE WITH TIME OF IMMERSION IN ALKALINE MEDIUM (NaOH SOLUTION)

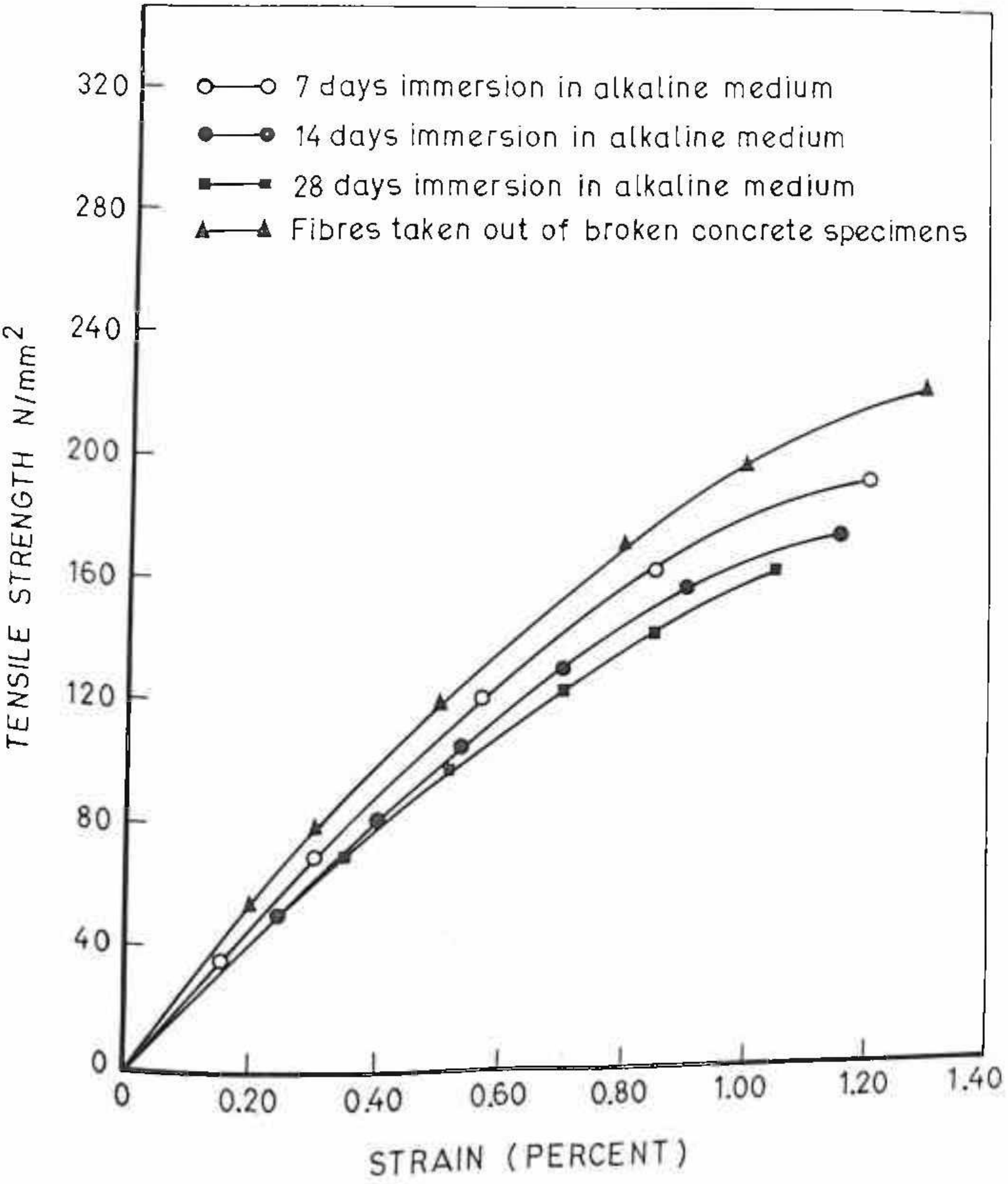


Fig. 4.4 STRESS-STRAIN CURVES OF SAN FIBRE IN ALKALINE MEDIUM

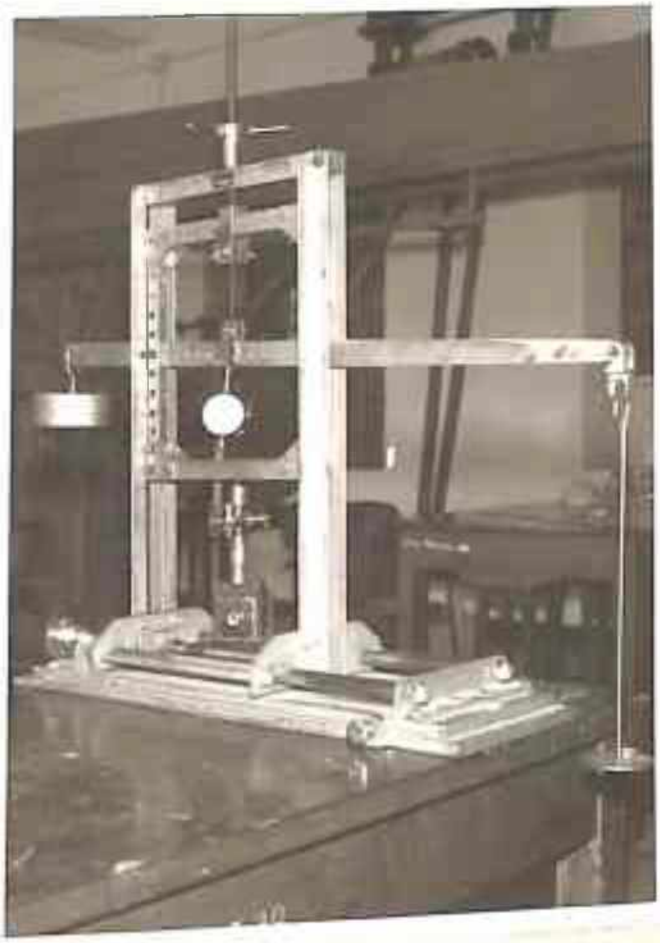


PLATE 4.1 TEST SET UP FOR DETERMINING TENSILE STRENGTH OF SAN FIBRE.

CHAPTER V

MECHANICS AND PROPERTIES OF FIBRE REINFORCED CONCRETE

5.1 Mechanics

When the fibre reinforced concrete specimens are loaded in flexure, two stages of behaviour in the load deformation curve have been generally observed as shown in Fig.5.1. The load deformation curve can be considered more or less linear up to point A. Beyond point A the curve is significantly nonlinear and reaches a maximum at point B. The load or the stress corresponding to the point A has been called first crack strength or elastic limit or proportional limit. The stress Corresponding to the point B has been termed as the ultimate strength. For a given mix, the fibre content, fibre geometry and the distribution of fibres are important to the properties of fibre reinforced concrete. However, the variables that are important for strength, durability and workability also have a significant influence on the properties. The variables that influence the bond, also affect the strength properties of fibre reinforced concrete.

Two mechanisms have been proposed for predicting the first crack strength or the proportional limit of the fibre reinforced concrete. One mechanism relates the proportional limit to the volume, orientation and length of the fibres while the other relates the first crack strength to the spacing of fibre reinforcements. Only the first mechanism, which is based on the law of mixtures of composite materials has been considered for theoretical analysis.

5.2 Composite Material Approach

When a plain mortar or plain concrete specimen is subjected to increasing load, cracking of the tensile zone immediately leads to failure of the specimen. However, it should be noted that cracking in concrete is not a discrete phenomenon. Careful measurements have revealed that a major crack which results in failure of a specimen is preceded by slow micro crack growth.

For fibre reinforced concrete the proportional limit is defined as that load below which a material is essentially linearly elastic. Below this limit the influence of matrix cracking can be neglected. The load deformation curve is more or less linear upto the proportional limit. It may be assumed that both the plain concrete and fibres behave elastically upto this load.

In a composite material consisting of a matrix reinforced with uniformly distributed unidirectional continuous fibres, it is assumed that, when the material is stressed, the fibres are firmly bonded so that no slipping occurs at the interface of the fibres and the matrix. The load acting on a composite section per unit area carried by the matrix and the fibres is expressed as

$$Sc = Sm\ Am + Sf\ Af \quad \dots\dots\dots\dots\dots\dots \quad (5.1)$$

Equation 5.1 may again be expressed in terms of the volume fractions of the constituent materials in the following form

$$Sc = Sm\ Vm + Sf\ Vf \quad \dots\dots\dots\dots\dots\dots \quad (5.1\ A)$$

In which Sc, Sm and Sf denote the average stresses in the composite section, the matrix and fibres respectively. Am and Af are the area fractions of the matrix and fibres respectively and Vm and Vf are the volume fractions of the matrix and fibres respectively.

Equation 5.1 is strictly valid for composites with continuous fibres, elastic behaviour of the components and no slippage between fibres and the matrix. Since fibres are finite in length there may be some micro cracking before the proportional limit because debonding may occur with fibres. As a result, this equation is only an upper bound solution for fibre reinforced concrete. Some experimental results support this conclusion[16].

In the case of unidirectional discontinuous fibre, a correction factor n, which is called length efficiency factor, is introduced to account for the stress distribution at the end portion of the fibres of finite length. It is given by

$$n = 1 - \frac{lc}{2l} \quad \dots\dots\dots\dots\dots \quad (5.2)$$

Where l is the length of the fibres and lc is the critical length of the San fibres, which was found out as follows.

Critical Fibre Length (lc)

Critical fibre length is defined as twice the "pullout" length (the minimum embedment length at which fibres are ruptured instead of pulled out under tensile forces).

In the present work, San fibres were embedded in Cement blocks. Embedded length varied from 5 mm to 15 mm with an increment of 1.0 mm. Fibres were pulled out after 28 days. The minimum embedded length at which fibres fractured instead of being pulled out came out to be 9 mm.

So the critical length of San fibre can be taken as 18 mm. This value is used for theoretical calculations. Length efficiency factor n for various fibre lengths has been presented in table 5.1

For a composite reinforced with randomly oriented and uniformly distributed fibres of short lengths, the strength can be expressed by introducing a constant f, called fibre orientation factor.

Then equation (5.1 A) can be modified as

$$Sc = Sm\ Vm + n\ f\ Sf\ Vf \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (5.3)$$

Where f is fibre orientation factor given by the equation[11]

$$f = \frac{3}{256\theta}(12\theta + 8 \sin 2\theta + \sin 4\theta) \quad \ldots\ldots (5.4)$$

$$\text{Where } \sin\theta = \frac{h}{l} \leq \pi/2 \quad \ldots\ldots\ldots\ldots\ldots\ldots (5.5)$$

For different values of θ, table 5.2 shows values of fibre orientation factor.

Equation 5.3 can be written separately for compression and tension as follows

$$Scc = Smc\ Vm + n\ f\ Sf\ Vf \quad \ldots\ldots\ldots\ldots\ldots (5.6)$$

and

$$Sct = Smt\ Vm + n\ f\ Sf\ Vf \quad \ldots\ldots\ldots\ldots\ldots (5.7)$$

Where

Scc and Sct are the compressive and tensile strength of the composite.

Smc and Smt are the compressive and tensile strength of the matrix.

Sf and Vf are the tensile strength and volume fraction of the fibres.

Using Hooke's law and noting that the matrix strain is equal to the strain of the composite, it follows equation 5.6 and 5.7 that

$$Ect = Emt\ Vm + n\ f\ Ef\ Vf \quad \ldots\ldots\ldots\ldots\ldots\ldots (5.8)$$

similarly for compression, equation 5.7 cam be written as

$$Ecc = Emc\ Vm + n\ f\ Ef\ Vf \quad .... (5.9)$$

Ecc and Ect are the modulus of elasticity of the composite in compression and tension, and Emc and Emt are the modulus of elasticity of the matrix in compression and tension.

Table 5.1

Values of Length Efficiency Factor(n) for Various Fibre Lengths

S.No.	Fibre length(l) in mm	Length efficiency factor (n)
1.	15	0.40
2.	20	0.55
3.	25	0.64
4.	30	0.70
5.	35	0.74

Table 5.2

Values of fibre orientation factor(f) for various values of θ

S.No.	Angle θ in degree	Fibre orientation factor(f)
1.	90	0.1406
2.	60	0.2084
3.	45	0.2599
4.	30	0.3150
5.	10	0.3674
6.	5	0.3731

It is important to realise that the natural fibres are not stiff like steel fibres, and they tend to align themselves in the direction, which is almost perpendicular to the plane of loading. This was verified from the inspection of the tested FRC specimens. Visual inspection indicates that the angle of inclination that the fibres make with the surface of the specimens varies from 10° to 30° and seldom exceeds 45°.

In the present investigation the value of angle θ is taken as 30° for the purpose of theoretical calculations for determination of composite strength.

5.3 Ultimate Strength

In fig 5.1 the load deflection curve is non linear beyond point A and reaches a maximum at point B i.e. the ultimate strength. Unlike conventionally reinforced concrete the maximum load is controlled primarily by fibers gradually pulling out, and the stress in the fibre at the ultimate load is subsequently less than the yield stress of the fibre. After the maximum load, the decrease in load with increasing deformations is much less for fibre reinforced concrete than that for plain concrete. As a result the total energy absorbed before complete separation of a beam is at least an order of magnitude higher for fibre reinforced concrete than for plain concrete. The energy is absorbed in debonding and stretching of fibres. The relative magnitude of each effect depends upon the stress-strain curve of the fibres themselves.

The ultimate strength for concrete reinforced with fibres depends upon the volume percentage of fibres and the fibre length.

At maximum load in flexure, part of the cross section of the matrix is cracked and some of the fibres may get partly debonded. The two important factors which influence the maximum load are volume percentage of fibres and their lengths. It has been shown that if segregation of fibres is avoided, the increase in volume percentage of fibres causes a more or less linear increase in the strength of the composite. For steel fibres, however, it has been observed that upto an aspect ratio of 150, the maximum load increased linearly with an increase in aspect ratio[16].

Based on this observation, the ultimate strength of the composite is given by

$$Sc = A\ Sm\ (1-Vf) + B\ Vf\ \frac{l}{d} \quad \ldots\ldots\ldots\ldots (5.16)$$

Where A and B are constants which can be determined by a plot of composite strength against Vf l/d.

Where l and d are the length and diameter of the fibres. It should be noted that the first term on the right hand side of the equation 5.16 represents the contribution of the matrix at the maximum load. The maximum value of the constant 'A' is unity. Constant 'B' depends on the bond strength between the fibres and the matrix and on the randomness of the fibres. Higher the bond strength and better aligned the fibres are in the direction of the load, the higher is the value of constant 'B'. The equation applies only when failure occurs by debonding of the fibres.

5.4 Fracture toughness

Toughness is defined as the total energy absorbed prior to complete separation of the specimen. This energy can be measured by taking the whole area under the complete tension or compression stress strain curve or by the area under the load deflection curve in flexure (fig 5.2). Energy absorbed can also be measured by an impact test. It is apparent that the toughness will depend on the type and rate of loading.

Toughness in plain concrete is related to crack growth. Concrete has greater toughness than cement paste alone because of more extensive microcrack growth in concrete due to the presence of the aggregates. When the fibres are present, the cracks can not extend without stretching and debonding the fibres. As a result additional energy is necessary before complete fracture of the fibre reinforced specimens.

Several investigators have shown that the toughness of the fibre reinforced concrete is at least an order of magnitude higher than that of plain concrete. Thus, increase in toughness is a significant improvement resulting from the addition of fibres.

The orientation of the fibres, their lengths and volume percentage influence the toughness of fibre reinforced concrete. In addition the stress-strain characteristics of fibre itself influence the total energy absorbed.

5.5 Factors Affecting Properties of Fibre Reinforced Concrete.

Fibre reinforced concrete as already stated can be defined as a composite material consisting of cement based matrix containing an ordered or random distribution of fibres. The fibres act as crack arresters that resist the growth of the flaws in the matrix, restraining them from enlarging under stress into cracks which eventually cause failure. By inhibiting the propagation of cracks originating from internal flaws, improvement in static and dynamic properties can be obtained, and thus fibres impart to the composite qualities of crack control, toughness, ductility and impact resistance.

The use of continuous aligned fibres in a cement matrix is fundamentally not different from conventional reinforced or prestressed concrete where the large diameter reinforcing bars or the smaller diameter prestressing wires behave analogously to the continuous aligned fibres. The phenomenon of multiple cracking and of composite action in such materials have been well established (fig 5.3). Obviously the highest strength characteristics are obtained when the fibres are aligned to resist the critical stresses, but then material becomes markedly anisotropic.

A more exciting challenging arrangement which has found a wider application is the use of short discontinuous fibres that are uniformly distributed in the matrix. It is true that with random orientation, not all the fibres are equally effective in crack control or in their strengthening and stiffening roles, nevertheless if sufficient strength and crack control improvement could otherwise be obtained, the other practical advantages of discontinuous fibres will outweigh the strength advantages of continuous aligned fibres.

The effective reinforcement of the matrix and the efficient transfer of stress between the matrix and the fibre depends upon many factors, ~~S~~some of which are intimately interdependent and exercise a profound but complex influence on the properties of the composite. These factors can be effectively considered in the following three categories

(a) Relative fibre matrix stiffness

(b) Fibre-matrix interfacial bond

(c) Strain compatibility between the fibres and the matrix

5.5.1 Relative Stiffness

For efficient stress transfer to the fibre, the elastic modulus of the matrix must be lower than that of the fibre. Low modulus fibres, such as natural fibres, nylon and polypropylene, are not likely to give much strength improvement; high modulus fibres such as metallic fibres (e.g. steel), glass, or crystalline inorganic fibres (e.g. asbestos) normally lead to strong composites. High strength high modulus fibres impart characteristics of strength and stiffness to the composite, whereas low modulus high elongation fibres are capable of large energy absorption characteristics, and impart a greater degree of toughness and resistance to impact and explosive loading. The former also contribute to these dynamic properties but to a lesser extent.

5.5.2 Fibre-Matrix Interfacial Bond

The interfacial bond between the matrix and the fibre determines the effectiveness of stress transfer from the matrix to the fibre. With randomly oriented, short, discrete fibres the interfacial bond that develops between the fibre and the matrix is not continuous, and becomes critical in defining the optimum fibre length-diameter ratio (the aspect ratio), and indeed, the volume content of the fibres for maximum improvement in tensile resistance. But a poorer interfacial bonding would show greater improvement of fracture toughness and impact resistance through energy dissipation and damping at the interfacial discontinuities. Fibre length and fibre diameter are thus critical in influencing static and dynamic properties.

If the interfacial bond is such that the composite failure occurs by fibre pull-out, then the matrix becomes the principal tensile load carrying element, and then only modest increases in tensile strength can be obtained. To achieve a truly two-phase composite action, the matrix must be so designed as to transfer load to the fibres so that they contribute fully to the composite strength. For short discontinuous fibres there is the additional criterion that the interfacial bond must be such that the anchorage length on any one side of the crack does not result in fibre pull-out.

5.5.3 Fibre-Matrix Strain Compatibility

Associated with the relative fibre-matrix stiffness and the interfacial bond is the need for strain compatibility between the fibre and the matrix. With cement-based matrices, the cracking and often the ultimate strain is of the order of 250 to 500 x 10^{-4} m/m, and since most fibres have far greater extensibility, bond failure occurs early, and hinders the efficient use of fibre reinforcement. The low cracking strain of the cement matrix also implies that reinforcement of the matrix can be achieved at fairly low volume fractions of the fibre.

5.5.4 Other Factors

Other factors such as the volume fraction of fibres and the orientation of fibres also influence the behaviour of fibre reinforced cementitious composites. The minimum or critical volume fraction below which increases in tensile strength cannot be expected, is with respect to static strength only. Even with low fibre volume fractions, the impact strength and resistance to crack propagation are considerably improved. The efficiency of the fibres depends on their orientation in space. With completely random orientation only about 41 per cent of the fibres are effective in reinforcing.

A major difficulty in fibre-reinforced cementitious systems is in incorporating quantities of fibre sufficient to achieve improvements in strength and at the same time making it economically viable. With conventional mixing techniques, the maximum volume of fibre that can be introduced is limited to 2 to 3 percent by volume, which in turn limits the strength properties that can then be achieved. New techniques of fibre incorporation such as spraying the fibres simultaneously with the matrix, modifying mixing techniques, using fibre-dispensing equipment, using special admixtures etc. may offer considerable improvements.

Traditional concrete mixes cannot be used with fibres. The size, shape, surface geometry, and volume fraction of the coarse aggregate all very much influence not only the rheological properties of the fibrous concrete but also its properties in the hardened state. Fibres in effect act as aggregates, and although they have a simple geometry their influence on the properties of the fresh concrete is complex. The inter-particle friction between fibres, and between fibres and aggregates would control the orientation and distribution of fibres, and consequently, the properties of the hardened material. Friction-reducing admixtures, and admixtures that improve the cohesiveness of the matrix, can significantly reduce the conglomeration of fibres and ensure the effectiveness and distribution of fibres.

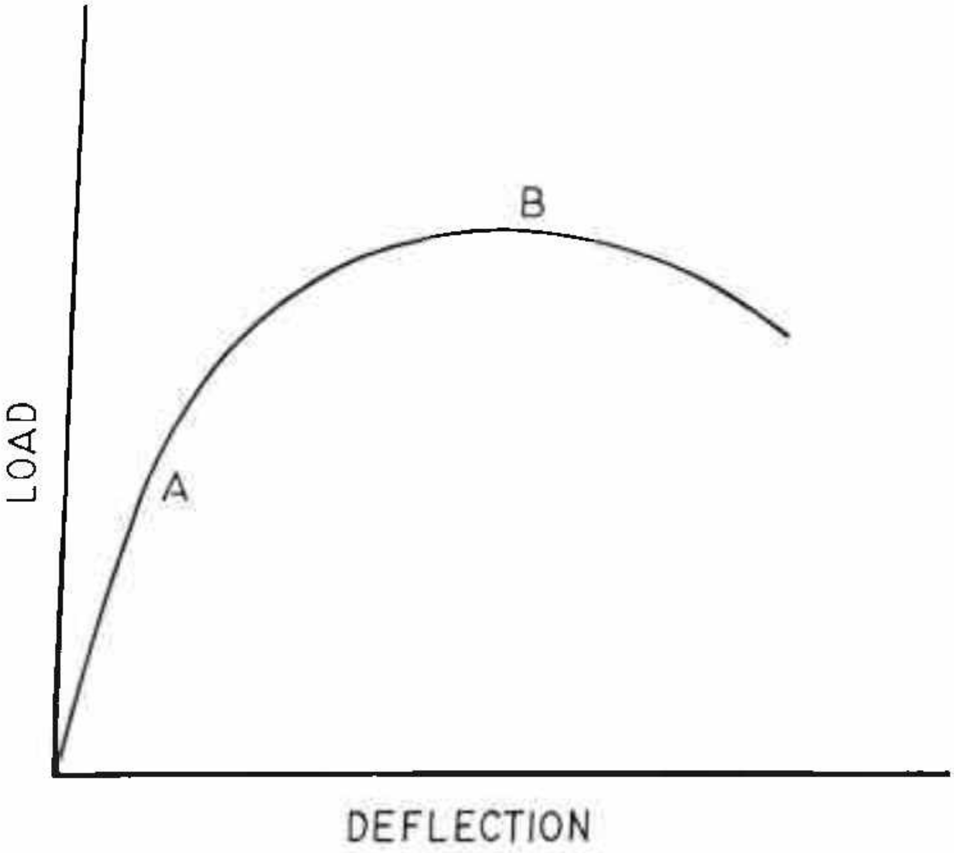


FIG. 5.1 LOAD-DEFLECTION CURVE FOR FIBRE REINFORCED CONCRETE

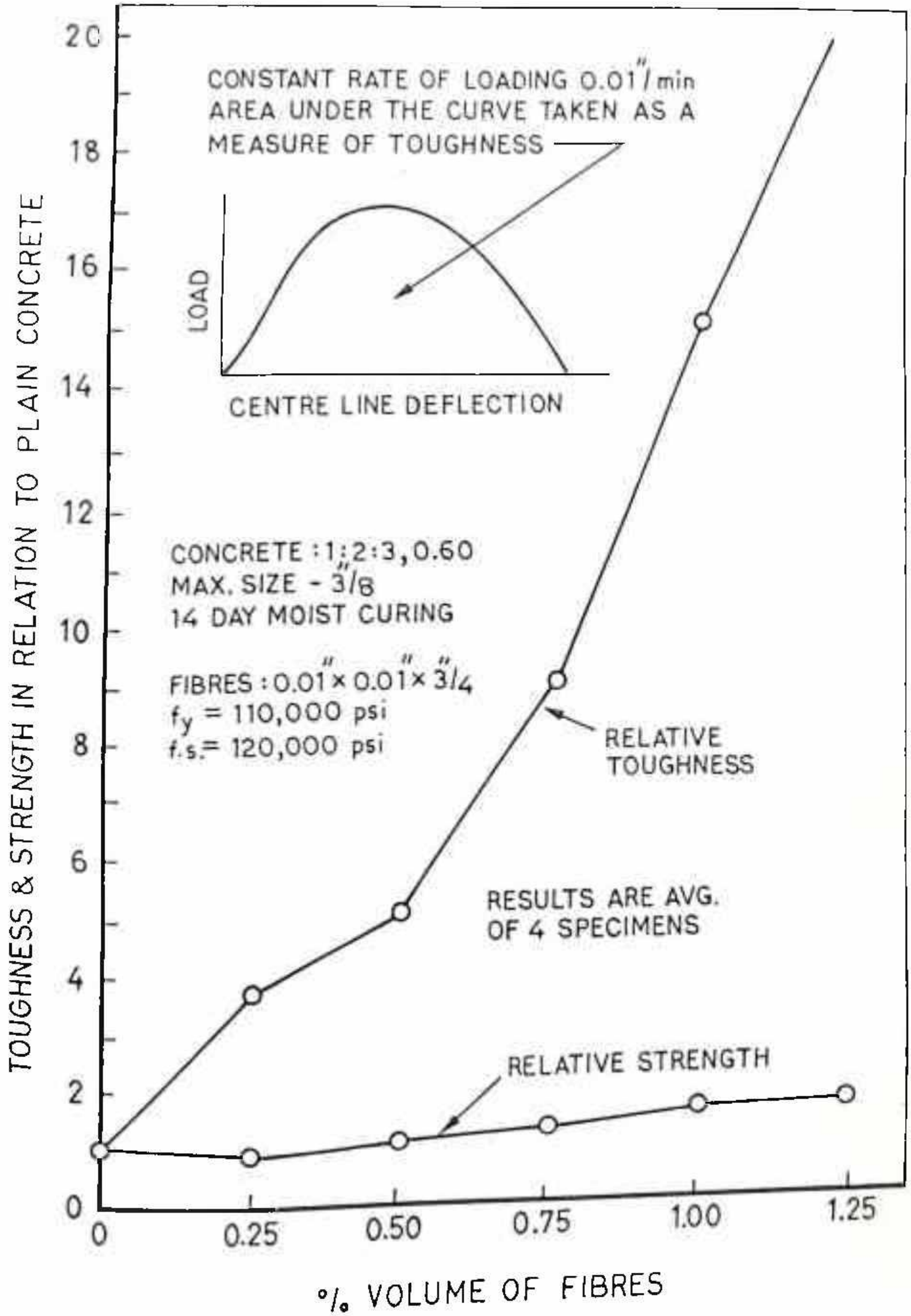
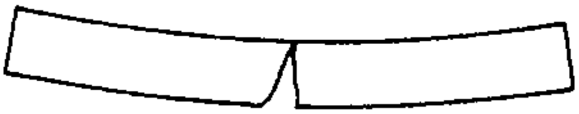
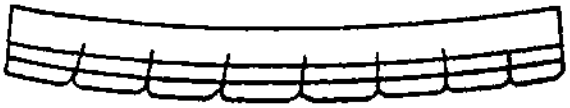


FIG.5.2 EFFECT OF VOLUME PERCENTAGE OF FIBRES ON TOUGHNESS IN FLEXURAL
(REFERENCE 16)



(a) NO FIBRES (PLAIN CONCRETE)

(b) PLAIN CONCRETE WITH SHORT DISCRETE FIBRES



(c) REINFORCING BARS OR PRESTRESSING WIRE FIBRES OR CONVENTIONAL CONTINUOUS REINFORCED WITH SHORT FIBRES

FIG.5.3 FLEXURAL FAILURE IN AN UNREINFORCED BEAMS AND IN BEAMS WITH FIBRES

CHAPTER - VI

COMPRESSIVE STRENGTH AND MODULUS OF ELASTICITY

In this chapter the effect of addition of san fibre to concrete on its compressive strength and modulus of elasticity has been discussed. At the beginning of this chapter, effect of san fibre on the workability of plain concrete has also been presented.

6.1 Workability

Workability of concrete can be measured by two methods.

1. Compaction factor test
2. Slump test

Compaction factor test is adopted to determine the workability of concrete, where nominal size of aggregate does not exceed 40 mm. It is based upon the definition, that workability is that property of the concrete which determines the amount of work required to produce full compaction. The test consists essentially of applying a standard amount of work to standard quantity of concrete and measuring the resulting compaction. The test is carried out as per specifications of IS: 1199-1956 to find out the workability of freshly prepared concrete. Workability gives an idea of the capability of being worked, i.e. idea to control the quantity of water in cement concrete mix to get uniform strength.

Fresh unsupported concrete flows to the sides and a sinking along the height takes place. This vertical settlement is known as slump and in this test fresh concrete is filled into a mould of specified shape and dimensions and the settlement or slump is measured when supporting mould is removed. Slump is a measure indicating the consistency or workability of cement concrete. Also the slump gives an idea of water/cement ratio needed for concrete to be used for different work. Concrete is said to be workable if it can be easily mixed, placed, compacted and finished. A workable concrete should not show any segregation or blending. Segregation is said to occur when course aggregate tries to separate out from the finer material and we get concentration of course aggregate at one place. This results in large voids, less durability and less strength. Bleeding of concrete is said to occur when excess water comes up at the surface of the concrete. This causes small pores in the mass of the concrete and is undesirable.

6.1.1 Discussion of Test Results

The workability of various types of fibre concrete was measured by compaction factor test and by slump test as per IS 1199-1959. The two test results are given tables 6.1 and 6.2

It is observed that as the fibre content increases, the workability of the mix decreases. The introduction of natural San fibre results in an apparent increase in the stiffness of the mix.

As, it is evident from table 6.1, for a constant volume percentage of fibres the compaction factor of the fibre concrete decreases with increase in the fibre length. Also compaction factor is lower for higher fibre concentrations with the same fibre length.

No measurable slump was noticeable for fibre concentration of 1.0 percent or more. It is evident from table 6.2 that for a constant volume percentage of fibres the slump decreases with increase in fibre length. Slump was also found to be lower for increased fibre concentrations with fibres of same length. It was observed that slump was practically zero for all fibre lengths beyond fibre concentrations of 1.25%.

Excessive balling of the fibres and failure of the concrete to penetrate the clumps of the fibres was observed. This difficulty was faced with practically all the lengths of fibres with fibre concentration of 1.25 and above. With lower volume percentages i.e. from 0.25 to 1.0, the balling was not appreciable to any fibre lengths.

6.2 Compressive Strength

Compressive strength of the san fibre reinforced concrete was determined experimentally using 150 mm cube specimens, tested after 28 days of continuous curing in water.

Results of the compression tests have been summarised in column 4 of the tables 6.3 to 6.8. Each one of these table presents compressive strength of the fibre concrete for a particular percentage of fibre concentration for all the five fibre lengths. Each value represents the average of results from 3 specimens.

6.2.1 Discussion of Test Results

(a) Effect of Volume Percentage of Fibres

Tables 6.3 to 6.8 clearly show that for any fibre length,there is increase in strength as the percentage of fibres is increased upto 0.75, but beyond 0.75% compressive strength decreases sharply as is clearly shown from fig 6.1.

(b) Effect of Fibre Length

For all the six volume percentages of fibres, compressive strength increases as the fibre length increases from 15 mm to 25 mm, beyond which the strength starts decreasing. Plots of compressive strength versus fibre lengths are shown in fig 6.2. for various volume fractions of fibres.

As is clear from fig 6.2, for each fibre percentage, the compressive strength is maximum when the fibre length is 25 mm. It is clear from tables 6.3 to 6.8 and fig 6.2 that presence of san fibre in plain concrete does not significantly affect the compressive strength of plain concrete upto fibre concentration of 0.75%, but beyond this percentage, strength decreases sharply. Maximum increase in compressive strength of fibre concrete. over plain concrete occurs with fibre content of 0.75% and fibre length of 25 mm. Increase is of the order of only 5.67%.

Maximum decrease in fibre concrete compressive strength over plain concrete is 24.79% which is for 35 mm fibre length and 1.5% of fibre concentration. Plate 6.1 shows fibre concrete cube after failure.

6.2.2 Comparison with Theory

The experimental values of the compressive strength of fibre concrete can be compared with the values determined theoretically by the law of mixture.

$$\mathrm{Scc} = \mathrm{Smc}\ \mathrm{Vm} + n\ f\ \ \mathrm{Sf}\ \mathrm{Vf} \qquad \ldots\ldots\ldots\ldots \qquad (5.6)$$

Where Scc and Smc are the compressive strength of the composite and matrix respectively.

Vm and Vf are the volume fraction of the matrix and fibres respectively

Sf is the tensile strength of the fibres.

n is length efficiency factor

f is fibre orientation factor.

Values of n and f are given in table 5.1 and 5.2 respectively.

The values of the compressive strength of the fibre concrete as determined by equation 5.6 are shown in column 6 of table 6.3 to 6.8.

A study of the column 4 and column 6 of the tables 6.3 to 6.8 indicates that experimental results and compressive strength values obtained from equation 5.6 seem in good agreement upto fibre content of 0.75%. But beyond 0.75% fibre concentration, experimental and theoretical results are not in good agreement. This happens because as per equation 5.6 strength should increase as percentage of fibres increases, but in reality strength decreases due to lumping problem which occurs significantly beyond 0.75% of the fibre content.

6.3 Modulus of Elasticity

The modulus of elasticity of concrete and its corresponding compressive strength are required in the design calculations of concrete structures. Modulus of elasticity can be determined by measuring the compressive strain, when a sample is subjected to a compressive load.

The modulus of elasticity which is also called secant modulus, is taken as the slope of the chord from the origin to some arbitrary point on the stress strain curve.

The secant modulus calculated in this study is for 33 percent of the maximum stress and is the average of the calculated values from 3 samples. Some times the modulus of elasticity is taken as the slope of the tangent at the origin or the slope of the tangent to the stress-strain curve drawn at some arbitrarily chosen point on the curve. The modulus so calculated is called tangent modulus. The tangent at the origin is, however difficult to draw accurately.

Based on the results of the compressive strength of fibre concrete, only 3 fibre percentages viz. 0.25%, 0.50% and 0.75%, and only 3 fibre lengths 20 mm, 25 mm and 30 mm have been considered for the determination of the modulus of elasticity of the composite.

The curves of uniaxial compressive stress versus compressive strain for plain concrete and fibrous concrete having different volume percentages and fibre lengths have been plotted and shown in fig 6.3 to 6.5. The values of the secant modulus for various combinations are shown in table 6.9.

6.3.1 Discussion of Test Results

The value of modulus of elasticity for plain concrete ranges from 1.4 x 10^4 N/mm^2 for low density concrete at early ages to 4.5 x 10^4N/mm^2 for high quality concrete at later ages. It increases with age and with reduction in water- cement ratio as does the strength. It is also affected appreciably by mix proportions. The aggregate has a higher elastic modulus than the cement paste and therefore, a leaner mix will give a higher value of the modulus than a richer mix with same water- cement ratio. The type and elastic modulus of aggregates also affect the elastic modulus of concrete.

Table 6.9 shows that the modulus of elasticity of fibre reinforced concrete is not appreciably different from that of plain concrete. The maximum difference of 2.2983% was obtained for fibres having length of 30 mm and volume fraction equal to 0.25%.

The maximum decrease was of the order of 2.7% for fibres of length 25 mm and a fibre concentration of 0.75% by volume.

6.3.2 Comparison with Theory

The experimental values of the modulus of elasticity can be compared with the values based on the theoretical equation following the law of mixture

orientation factor and length efficiency factor.

$$Ecc = Emc\ Vm + n\ f\ Ef\ \ Vf \ \ldots\ldots\ldots\ldots\ldots \quad (5.8)$$

Where Ecc and Emc are the modulus of elasticity of the composite and matrix respectively

Vm and Vf are the volume fraction of the matrix and fibres respectively

Sf is the tensile strength of the fibres

n is length efficiency factor

f is fibre orientation factor

Values of n and f are given in tables 5.1 and 5.2 respectively

The values of the modulus of elasticity of the fibre reinforced concrete composite as obtained from equation 5.8 are shown in column 8 of table 6.9 and comparison of the two values i.e. experimental and theoretical is shown in column 9. It is clear from column 9 of the table 6.9 that maximum deviation from experimental values is 2.55% for fibre length of 30 mm and fibre percentage of 0.75%.

Table 6.1

Workability of San Fibre Reinforced Concrete by Compaction Factor Method.

S.N.	Test Series	Specimen Types	Compaction factor
1.	A	Plain concrete	0.926
2.	B1	FRC-15-0.25	0.912
3.	B2	FRC-20-0.25	0.903
4.	B3	FRC-25-0.25	0.906
5.	B4	FRC-30-0.25	0.885
6.	B5	FRC-35-0.25	0.896
7.	C1	FRC-15-0.50	0.865
8.	C2	FRC-20-0.50	0.854
9.	C3	FRC-25-0.50	0.856
10.	C4	FRC-30-0.50	0.849
11.	C5	FRC-35-0.50	0.823
12.	D1	FRC-15-0.75	0.842
13.	D2	FRC-20-0.75	0.843
14.	D3	FRC-25-0.75	0.825
15.	D4	FRC-30-0.75	0.806
16.	D5	FRC-35-0.75	0.792
17.	E1	FRC-15-1.00	0.813
18.	E2	FRC-20-1.00	0.804
19.	E3	FRC-25-1.00	0.796
20.	E4	FRC-30-1.00	0.785
21.	E5	FRC-35-1.00	0.767
22.	F1	FRC-15-1.25	0.808

Table 6.1 (Continued)

S.N.	Test Series	Specimen Types	Compaction factor
23.	F2	FRC-20-1.25	0.807
24.	F3	FRC-25-1.25	0.785
25.	F4	FRC-30-1.25	0.766
26.	F5	FRC-35-1.25	0.777
27.	G1	FRC-15-1.50	0.785
28.	G2	FRC-20-1.50	0.778
29.	G3	FRC-25-1.50	0.768
30.	G4	FRC-30-1.50	0.766
31.	G5	FRC-35-1.50	0.767

Table 6.2
Workability of San Fibre Reinforced Concrete by Slump Test Method

S.N.	Test Series	Specimen Types	Slump (mm)
1.	A	Plain concrete	23.0
2.	B1	FRC-15-0.25	14.0
3.	B2	FRC-20-0.25	13.0
4.	B3	FRC-25-0.25	13.5
5.	B4	FRC-30-0.25	11.0
6.	B5	FRC-35-0.25	9.5
7.	C1	FRC-15-0.50	11.5
8.	C2	FRC-20-0.50	11.0
9.	C3	FRC-25-0.50	9.5
10.	C4	FRC-30-0.50	8.0
11.	C5	FRC-35-0.50	7.0
12.	D1	FRC-15-0.75	10.0
13.	D2	FRC-20-0.75	8.0
14.	D3	FRC-25-0.75	6.5
15.	D4	FRC-30-0.75	5.0
16.	D5	FRC-35-0.75	4.0
17.	E1	FRC-15-1.00	9.0
18.	E2	FRC-20-1.00	7.5
19.	E3	FRC-25-1.00	5.5
20.	E4	FRC-30-1.00	4.0
21.	E5	FRC-35-1.00	4.0

Beyond 1.00% of fibre concentration slump was zero for practically all the fibre lengths

Table 6.3

Compressive Strength of San Fibre Reinforced Concrete (Fibre 0.25%)

S.N.	Test Series	Type of specimens	Cube strength N/mm^2	Cube strength ratio	Cube strength as per equation 5.6 N/mm^2	Cube strength $\frac{\text{TEST}}{\text{THEORY}}$
1	2	3	4	5	6	7
1.	A	Plain concrete	15.330	1.0000	15.330	1.0000
2.	B1	FRC-15-0.25	14.544	0.9480	15.340	0.9981
3.	B2	FRC-20-0.25	15.050	0.9810	15.370	0.9791
4.	B3	FRC-25-0.25	15.300	0.9980	15.380	0.9947
5.	B4	FRC-30-0.25	15.000	0.9780	15.392	0.9745
6.	B5	FRC-35-0.25	14.350	0.9360	15.398	0.9319

Table 6.4

Compressive Strength of San Fibre Reinforced Concrete (Fibre 0.50%)

S.N.	Test Series	Type of specimens	Cube strength N/mm^2	Cube strength ratio	Cube strength as per equation 5.6 N/mm^2	Cube strength $\frac{\text{TEST}}{\text{THEORY}}$
1	2	3	4	5	6	7
1.	A	Plain concrete	15.330	1.0000	15.330	1.0000
2.	C1	FRC-15-0.50	14.850	0.9680	15.368	0.9662
3.	C2	FRC-20-0.50	15.250	0.9940	15.411	0.9895
4.	C3	FRC-25-0.50	15.600	1.0176	15.437	1.0105
5.	C4	FRC-30-0.50	15.200	0.9915	15.454	0.9835
6.	C5	FRC-35-0.50	14.700	0.9580	15.466	0.9504

Table 6.5

Compressive Strength of San Fibre Reinforced Concrete (Fibre 0.75%

S.N.	Test Series	Type of specimens	Cube strength N/mm^2	Cube strength ratio	Cube strength as per equation 5.6 N/mm^2	Cube strength TEST ------ THEORY
1	2	3	4	5	6	7
1.	A	Plain concrete	15.330	1.0000	15.330	1.0000
2.	D1	FRC-15-0.75	15.500	1.0110	15.388	1.0072
3.	D2	FRC-20-0.75	15.900	1.0371	15.452	1.0289
4.	D3	FRC-25-0.75	16.200	1.0567	15.490	1.0458
5.	D4	FRC-30-0.75	15.750	1.0270	15.517	1.0150
6.	D5	FRC-35-0.75	14.200	0.9915	15.536	0.9783

Table 6.6

Compressive Strength of San Fibre Reinforced Concrete (Fibre 1.00%)

S.N.	Test Series	Type of specimens	Cube strength N/mm^2	Cube strength ratio	Cube strength as per equation 5.6 N/mm^2	Cube strength $\frac{\text{TEST}}{\text{THEORY}}$
1	2	3	4	5	6	7
1.	A	Plain concrete	15.330	1.0000	15.330	1.0000
2.	E1	FRC-15-1.00	13.800	0.9001	15.406	0.8957
3.	E2	FRC-20-1.00	14.25	0.9290	15.492	0.9198
4.	E3	FRC-25-1.00	14.50	0.945	15.544	0.9328
5.	E4	FRC-30-1.00	14.05	0.9165	15.579	0.9018
6.	E5	FRC-35-1.00	13.40	0.8741	15.603	0.8588

Table 6.7

Compressive Strength of San Fibre Reinforced Concrete (Fibre 1.25%)

S.N.	Test Series	Type of specimens	Cube strength N/mm^2	Cube strength ratio	Cube strength as per equation 5.6 N/mm^2	Cube strength $\frac{\text{TEST}}{\text{THEORY}}$
1	2	3	4	5	6	7
1.	A	Plain concrete	15.330	1.0000	15.330	1.0000
2.	F1	FRC-15-1.25	12.850	0.8382	15.426	0.8330
3.	F2	FRC-20-1.25	13.250	0.8643	15.534	0.8529
4.	F3	FRC-25-1.25	13.440	0.8761	15.599	0.8615
5.	F4	FRC-30-1.25	13.020	0.8493	15.642	0.8323
6.	F5	FRC-35-1.25	12.45	0.8121	15.673	0.7943

Table 6.8

Compressive Strength of San Fibre Reinforced Concrete (Fibre 1.50%)

S.N.	Test Series	Type of specimens	Cube strength N/mm^2	Cube strength ratio	Cube strength as per equation 5.6 N/mm^2	Cube strength $\frac{\text{TEST}}{\text{THEORY}}$
1	2	3	4	5	6	7
1.	A	Plain concrete	15.330	1.0000	15.330	1.0000
2.	G1	FRC-15-1.50	11.850	0.7729	15.446	0.7671
3.	G2	FRC-20-1.50	12.240	0.7984	15.575	0.7858
4.	G3	FRC-25-1.50	12.510	0.8160	15.653	0.7972
5.	G4	FRC-30-1.50	12.050	0.7860	15.705	0.7672
6.	G5	FRC-35-1.50	11.530	0.7521	15.742	0.7324

Table 6.9

Modulus of Elasticity of San Fibre Reinforced Concrete

S.N.	Test Series	Type of specimnen	Cylindrical strength N/mm^2	33% of Maximum compressive strength N/mm^2
1	2	3	4	5
1.	A	Plain concrete	12.26	5.058
2.	B2	FRC-20-0.25	11.55	4.966
3.	C2	FRC 20 0.50	12.50	5.032
4.	D2	FRC-20-0.75	12.56	5.247
5.	B3	FRC-25-0.25	12.23	5.049
6.	C3	FRC 25-0.50	13.02	5.148
7.	D3	FRC-25-0.75	13.13	5.346
8.	B4	FRC-30-0.25	12.30	4.950
9.	C4	FRC-30-0.50	11.85	5.016
10.	D4	FRC-30-0.75	12.28	5.197

Table 6.9 (Continued)

Strain at 33% of maximum stress (Percent)	Secant modulus at 33% maximum stress N/mm^2 x 10^4	Modulus of elasticity as per equation 5.8 $N/mm^2 x 10^4$	$\frac{E_{Test}}{E_{Theory}}$
6	7	8	9
.0248	1.9750	1.975	1.0000
.0248	2.002	1.970	1.0162
.0256	1.9656	1.9663	0.9996
.0272	1.9290	1.9625	0.9829
.0256	1.9722	1.9709	1.0006
.0264	1.9500	1.9669	0.9914
.0278	1.9230	1.9629	0.9796
.0254	2.0204	1.9715	1.0229
.0252	1.9900	1.9671	1.0116
.0270	1.9240	1.9631	0.9745

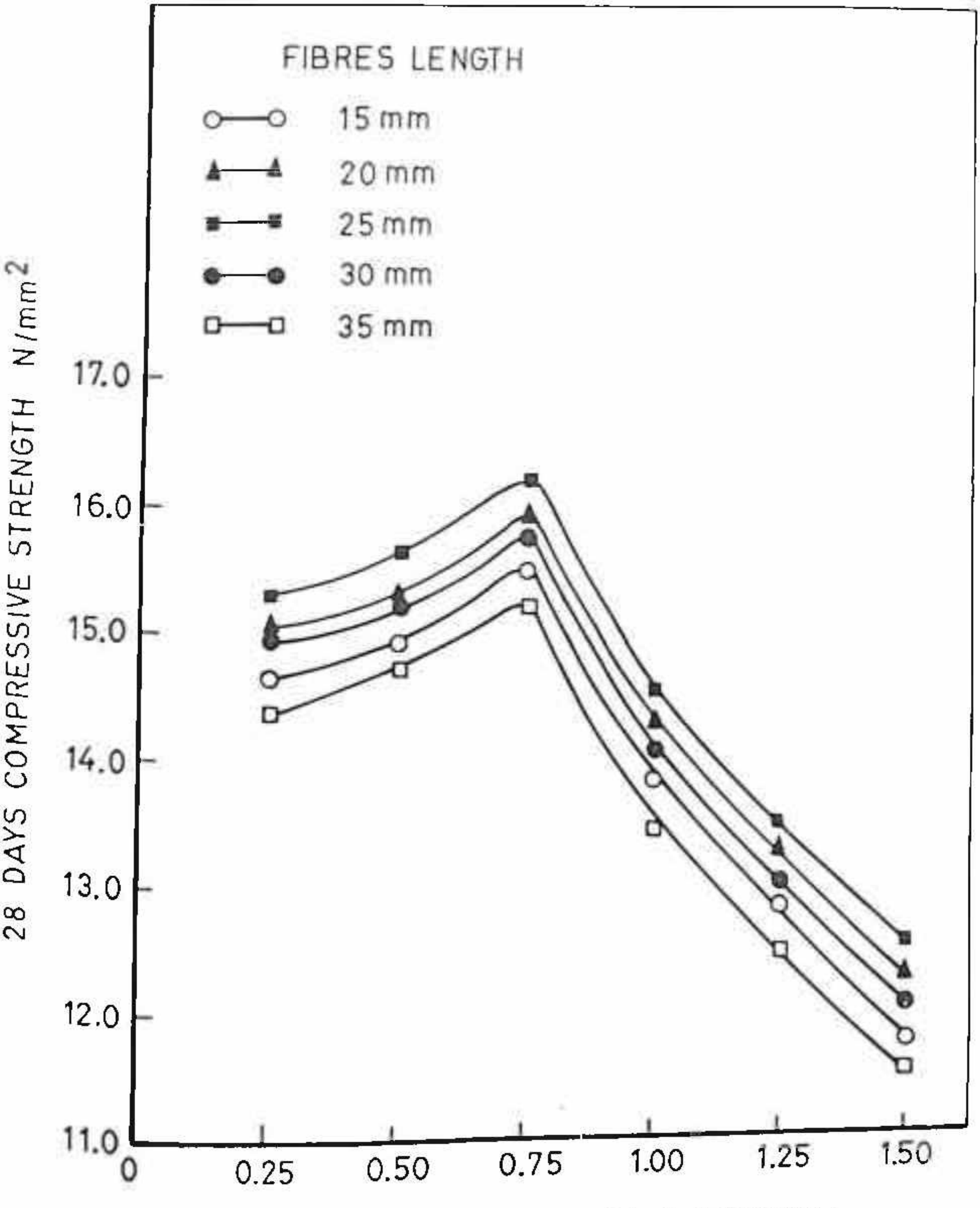


FIG.6.1 EFFECT OF VOLUME PERCENTAGE OF FIBRES ON CUBE COMPRESSIVE STRENGTH

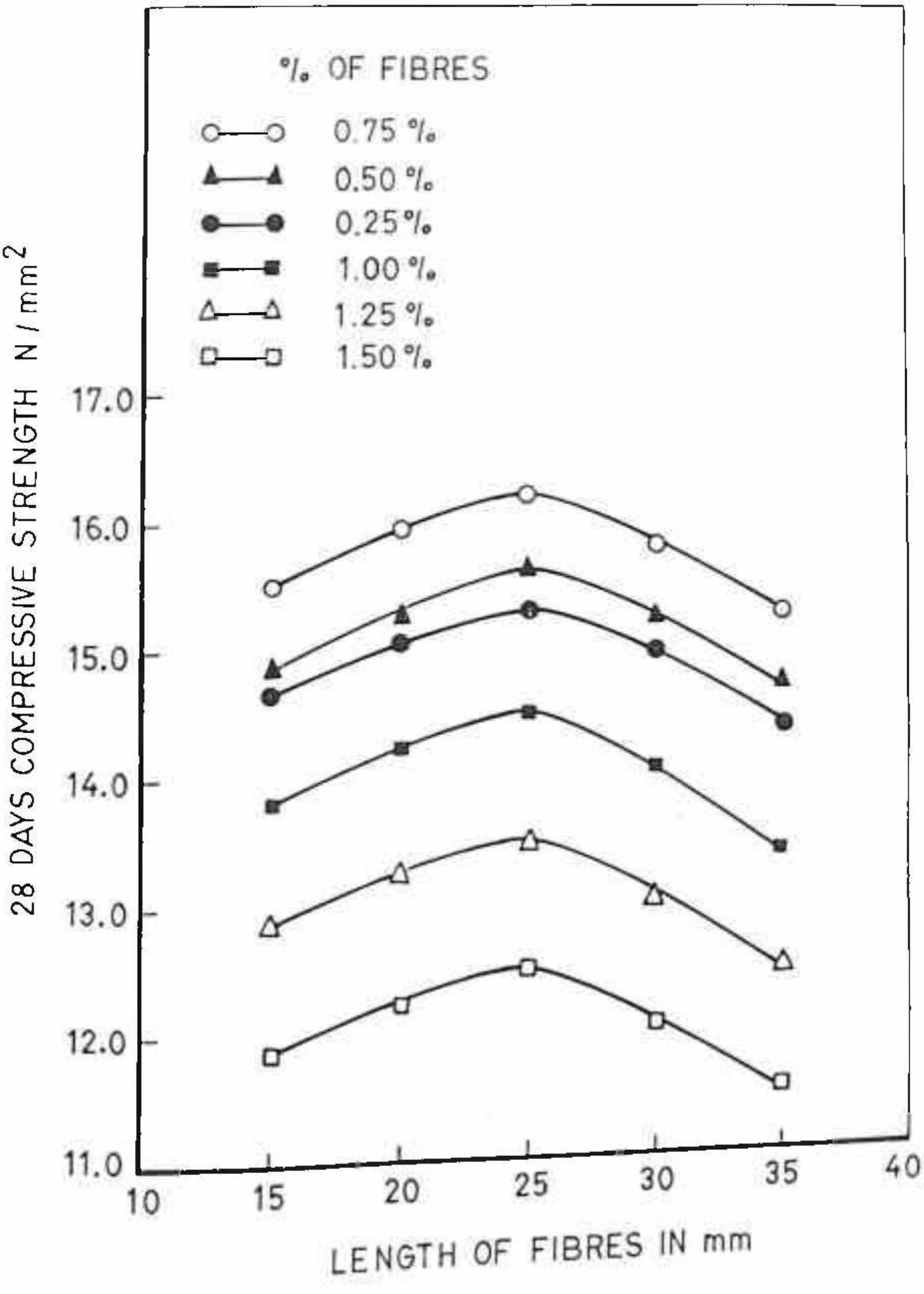


FIG.6.2 EFFECT OF LENGTH OF FIBRES ON CUBE COMPRESSIVE STRENGTH

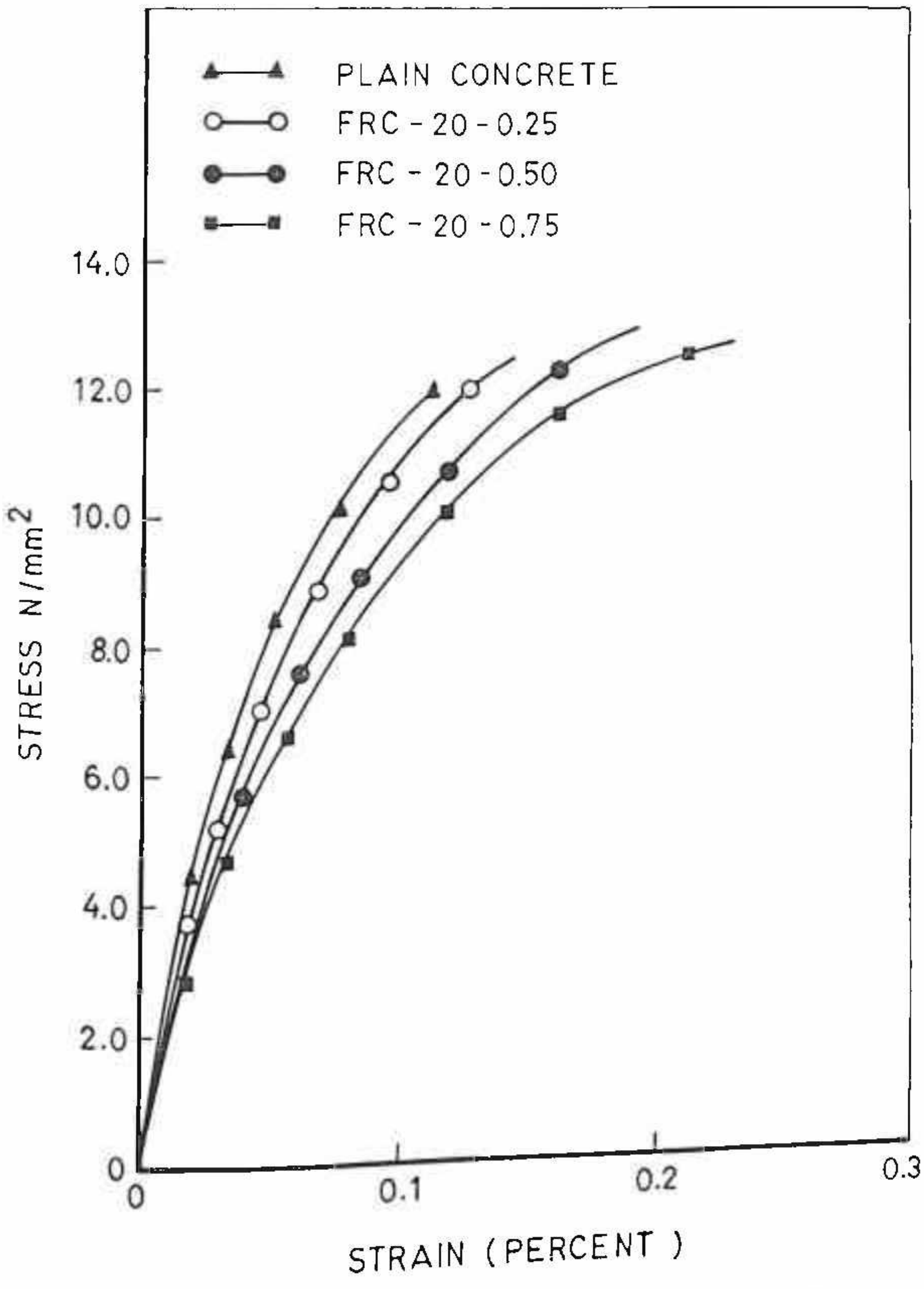


FIG. 6.3 COMPRESSIVE STRESS-STRAIN CURVES OF SAN FIBRE REINFORCED CONCRETE

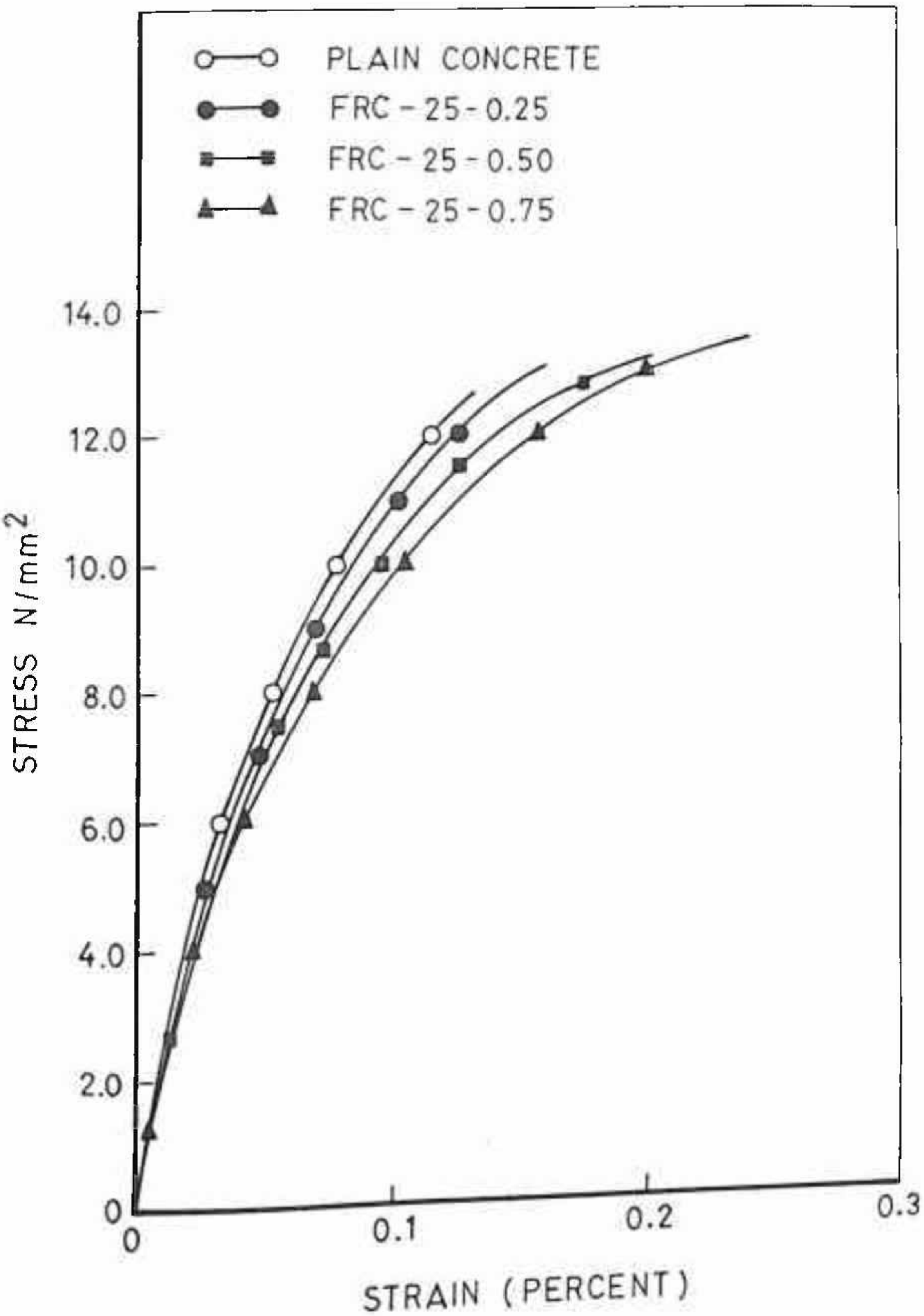


FIG. 6.4 COMPRESSIVE STRESS-STRAIN CURVES OF SAN FIBRE REINFORCED CONCRETE

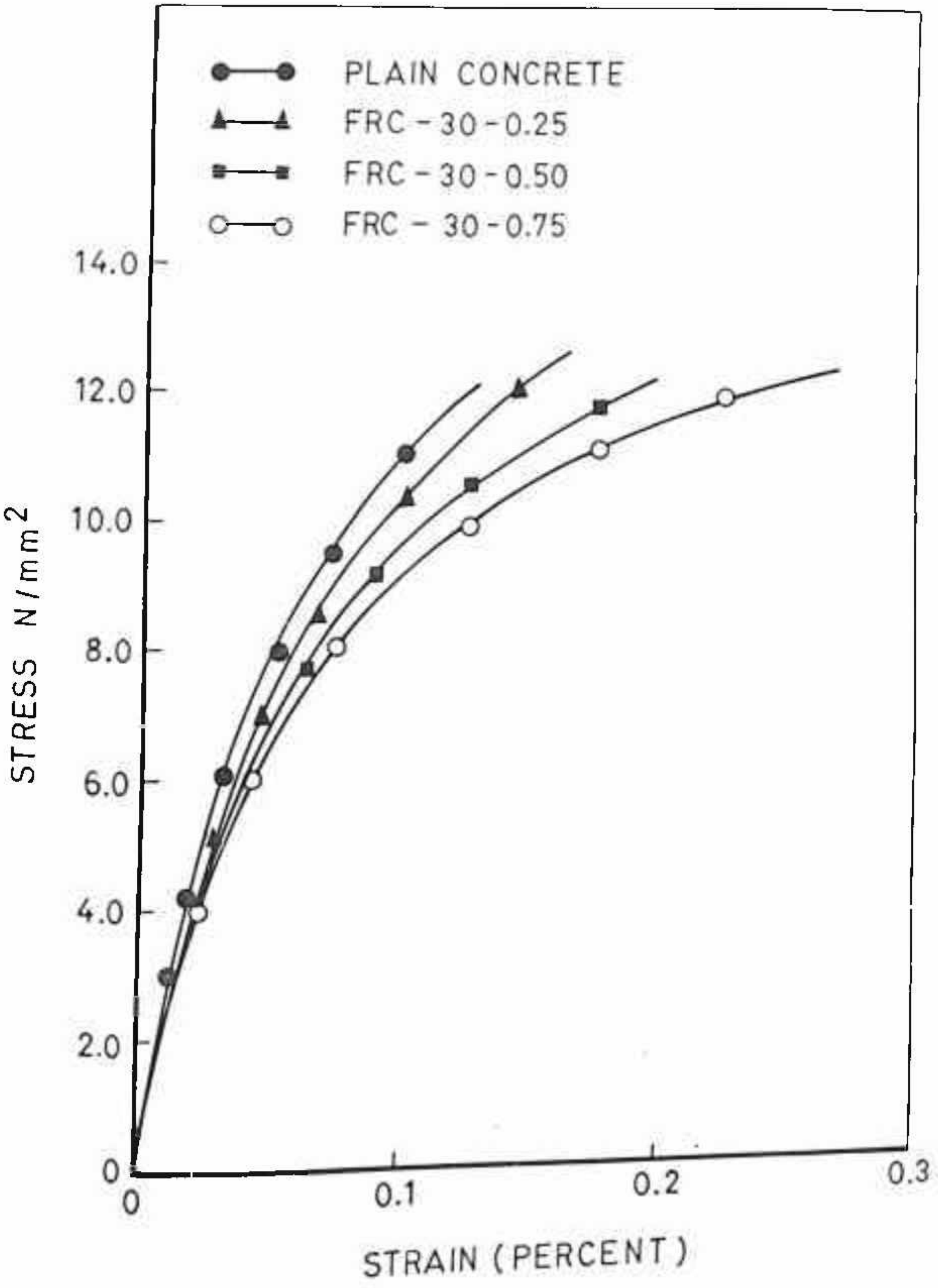


FIG. 6.5 COMPRESSIVE STRESS-STRAIN CURVES OF SAN FIBRE REINFORCED CONCRETE

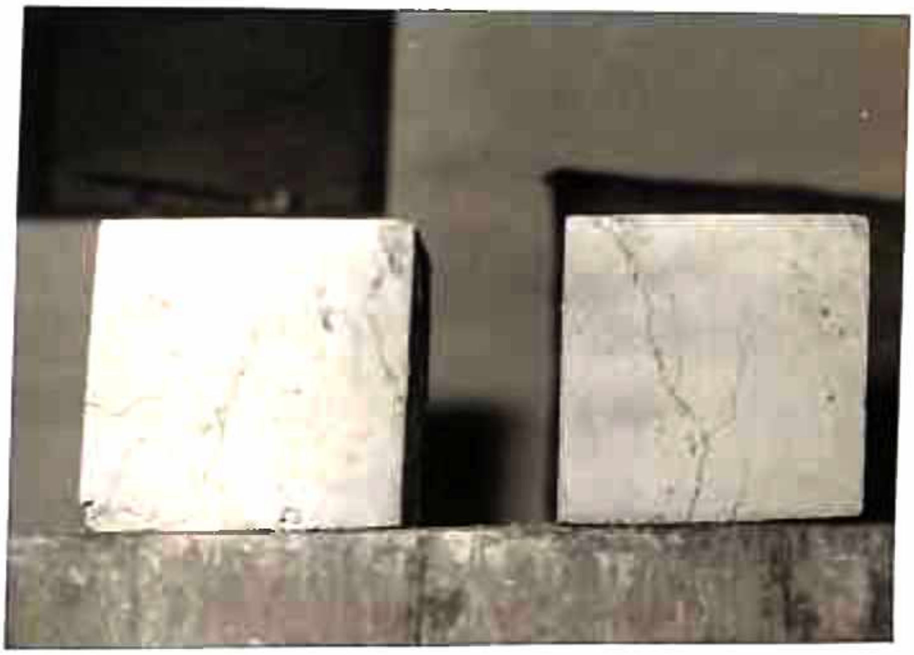


PLATE 6.1 PLAIN CONCRETE CUBES AFTER FAILURE.

PLATE 6.2 SAN FIBRE REINFORCED CONCRETE CUBES AFTER FAILURE.

CHAPTER - VII

TENSILE STRENGTH

In this chapter, split tensile strength, flexural tensile strength, deflection in flexural tension and energy absorption capacity of san fibre reinforced concrete have been presented.

7.1 Split Tensile Strength (Indirect Tensile Strength)

Split tensile strength of the San reinforced concrete were determined. Results were obtained on cylindrical specimens (150 mm dia and 300 mm long), tested after 28 days of continuous curing in water.

Results of the split tensile test have been presented in column 4 of the table 7.1 to 7.6. Each of these table represents split tensile strength of the fibre concrete for a particular percentage of fibre concentration for all the five fibre lengths. Each results represents the average of 3 specimens.

7.1.1 Discussion of Test Results

(a) Effect of Volume Percentage of Fibres

Table 7.1 to 7.6 clearly show that there is an increase in strength, as the percentage of fibres is increased upto 0.75% for all the fibre lengths, but beyond 0.75% of the fibre content, split tensile strength starts decreasing as it is also clearly evident from Fig. 7.1.

(b) Effect of Fibre Length

For all the six volume percentages of fibres split tensile strength increases for fibre length of 15 to 25 mm but for fibre length of 30 to 35 mm, strength starts decreasing.

As is clear from Fig. 7.2, for the fibre of all lengths, maximum split tensile strength occurs only at 0.75% of fibre content. The maximum increase in split tensile strength is 19.03% at 0.75% of the fibre content and 25 mm fibre length. The maximum decrease in split tensile strength is 17.33% at 1.5% fibre content and 35 mm fibre length.

(c) Mode of Failure and Crack Pattern

The increase in the percentage of fibres affected the type of failure in the material. The plain concrete specimens failed in the typical planer mode in the sense that crack was nearly central and almost vertical joining top and bottom of the specimen, indicating characteristics of a brittle material. The failure pattern of the fibre concrete specimen was not same as that of plain concrete specimens and the crack was not as vertical as in case of plain concrete specimens. The fractured surface of the cylinder shows that the failure of the fibrous specimens was due to fibre pull out in general. Plate 7.1 & 7.2 show the crack patterns in plain and fibre reinforced concrete cylinders respectively.

7.1.2 Comparison with Theory

The experimental values of the split tensile strength of fibre concrete can be compared with the values obtained from theory based on law of mixture.

The following equation can be used here

Sct = Smt Vm + n f Sf Vf .... (5.7)

Sct and Smt as defined earlier are the tensile strength of the composite and matrix respectively in indirect tension.

Vm and Vf are the volume fraction of the matrix and fibres respectively.

Sf is the tensile strength of the fibres.

n is length efficiency factor

f is fibre orientation factor

Values of n and f have been presented in table 5.1 and 5.2 respectively.

The values of the split tensile strength of the fibre composite as given by equation 5.7 are shown in column 6 of tables 7.1 to 7.6.

A study of the column 7 of tables 7.1 to 7.6 indicates that experimental results and split tensile strength values, obtained from equation 5.7 are in good agreement upto fibre content of 0.75%. But beyond 0.75% of the fibre content, experimental and theoretical values do not agree, because, though in accordance with equation 5.7 split tensile strength should increase as percentage of fibres increases, it in fact decreases due to lumping in concrete, which is more prominent after 0.75% of the fibre content.

7.2 Flexural Tensile Strength (Modulus of Rupture)

As seen earlier, results of the split tensile strength of the fibre concrete increases upto 0.75% of fibre content and beyond this the strength starts reducing. Also suitable lengths of fibres are seem to be 20 mm, 25 mm and 30 mm.

So, for investigating the effect of fibre on flexural strength of the composite, specimens were cast with three fibre percentages viz. 0.25%, 0.50% and 0.75% and each with three fibre lengths only viz. 20 mm, 25 mm, and 30 mm.

The experimental results of the flexural strength of the plain concrete and fibre concrete are presented in Table 7.7.

7.2.1 Discussion of Test Results

Table 7.7 shows load at first crack, first cracking strength, load at complete failure, and ultimate failure strength.

(a) Influence of Fibre Reinforcement on the on-set of Flexural Cracking

The influence of fibres on the on set of flexural cracking and on the ultimate strength is shown in the fig 7.3 which contains plots of first crack strength ratio and ultimate strength ratio (first crack / ultimate strength of fibre concrete to that of plain concrete) against volume percentage of fibres. These curves show that addition of natural san fibre increases the strength marginally at the on-set of flexural cracking of the concrete matrix.

For a composite containing 0.25% fibres, the increase in first cracking strength is 2.12%, 5.11% and 4.55% for fibre lengths of 20 mm, 25 mm and 30 mm respectively.

In case of composite having 0.50% of fibres, there is an improvement in first cracking strength of 5.00%, 8.62% and 6.96%, for fibre lengths of 20 mm, 25 mm, and 30 mm respectively.

Similarly, for a composite with 0.75% fibres, an increase of 8.56%, 10.71% and 7.75% in the first cracking strength is found with fibre lengths of 20 mm, 25 mm and 30 mm respectively.

(b) Influence of Fibres on Ultimate Flexural Strength

The effect of san fibre on ultimate flexural strength is shown in Fig. 7.3.

For a composite of 0.25% fibre content increase in ultimate strength is 5.90%, 7.33% and 7.01% for fibre lengths of 20 mm, 25 mm and 30 mm respectively. For 0.50% fibre content the corresponding increase of 9.25%, 10.18% and 8.00%, and for 0.75% fibre content 11.79%, 12.78% and 8.60%. respectively.

(c) Relation Between First Crack and Ultimate Flexural Strengths

The influence of fibres on the ratio of the ultimate to first crack modulus of rupture for plain and fibre reinforced concrete is shown in Column 10 of table 7.7. With the addition of fibres, the ratio of the ultimate to first crack flexural strength increases marginally for all fibre lengths. The maximum value of this being 1.0404 at fibre volume percentage of 0.50 and fibre length of 20 mm.

(d) Mode of Failure and Crack Pattern

The plain concrete specimens failed instantaneously indicating the brittleness of the material. The fibre concrete specimens failed with ample warning indicating the ductility of the material. The fibre reinforced specimens showed sufficient resistance to complete failure indicating thereby sufficient flexural stiffness.

The width of flexural crack in case of fibrous specimens was much smaller as compared to plain specimens at maximum load. Almost all the beams developed one major crack near the centre of the specimens. It was observed that the cracks did not travel exactly vertically but with slight change in direction. Plate 7.3 shows the crack pattern of plain concrete beam where as plates 7.4 to 7.6 show the same for fibre reinforced concrete.

7.2.2. Comparison with Theory

Experimental values of the flexural tensile strength of the fibre concrete can be compared with the values based on law of mixture.

The following equation can be used

$$Sct = Smt\ Vm + n\ f\ Sf\ Vf \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (5.7)$$

As indicated earlier, Sct and Smt are the flexural tensile strength of the composite and matrix respectively.

Vm and Vf are the volume fraction of the matrix and fibres respectively.

Sf is the tensile strength of the fibres.

n and f are the length efficiency factor and fibre orientation factor respectively.

Tables 5.1 and 5.2 gives the values of n and f respectively.

The values of the flexural tensile strength of the fibre composite as obtained from equation 5.7 are shown in column 11 of table 7.7. Column 12 of table 7.7 indicates that experimental values and values given by equation 5.7 are in good agreement. The maximum deviation is 4.98% for fibre concentration of 0.75% and fibre length 20 mm.

7.3 Deflection in Flexural Tension

Deflections were measured at every 1000 N increment until the ultimate failure occurred. Ultimate crack deflections are listed in column 4 of Table 7.8. Each value is the average of three specimens.

The deflection increases more or less linearly as the percentage of fibres varies from 0.25 to 0.75 percent for each of the three fibre lengths viz. 20 mm, 25 mm, and 30 mm. The maximum value of the deflection corresponding to the ultimate load, was obtained for the composite having fibres length 30 mm and volume percentage 0.75%. The load deflection curve for plain and fibre concrete are plotted in figures 7.4 to 7.6.

7.4 Energy Absorption Capacity (Fracture Toughness)

The area under the load deflection curve of a flexural specimen is a measure of energy absorption capacity of the specimen. This area may also be considered to give a measure of ductility and indirectly the fracture toughness of the material.

The energy absorption capacity as obtained from the area under the load deflection curve for all flexural specimens is listed in column 5 of table 7.8. and column 6 gives the ratio of the energy absorption capacity of the fibre reinforced concrete to that of plain concrete.

Fig 7.7 shows the variation of fracture toughness ratio with volume percentage of the fibres. It can be seen that the minimum energy absorption capacity of 400.00 N-mm occurs for plain concrete mix and it increases linearly with fibre volume. The highest energy absorption capacity of 1235.30 N mm occurred with a fibre volume percentage of 0.75 and fibre length of 30 mm.

Table 7.1

Split Tensile Strength of San Fibre Reinforced Concrete (Fibre 0.25%)

S.N.	Test Series	Type of specimens	Split tensile strength N/mm^2	Split tensile strength ratio	Split tensile strength as per Equation 5.7 N/mm^2	Strength $\frac{\text{TEST}}{\text{THEORY}}$
1	2	3	4	5	6	7
1.	A	Plain concrete	1.6970	1.0000	1.6970	1.0000
2.	B1	FRC-15-0.25	1.7500	1.0312	1.7500	1.0000
3.	B2	FRC-20-0.25	1.8200	1.0724	1.8466	0.9855
4.	B3	FRC-25-0.25	1.8800	1.1078	1.7840	1.0538
5.	B4	FRC-30-0.25	1.8250	1.0754	1.7934	1.0176
6.	B5	FRC-35-0.25	1.7550	1.0341	1.799	0.9755

Table 7.2

Split Tensile Strength of San Fibre Reinforced Concrete (Fibre 0.50%)

S.N.	Test Series	Type of specimens	Split tensile strength N/mm^2	Split tensile strength ratio	Split tensile strength as per Equation 5.7 N/mm^2	Strength TEST ----- THEORY
1	2	3	4	5	6	7
1.	A	Plain concrete	1.6970	1.0000	1.6970	1.0000
2.	C1	FRC-15-0.50	1.8250	1.0754	1.8030	1.0122
3.	C2	FRC-20-0.50	1.9000	1.1196	1.8466	1.0289
4.	C3	FRC-25-0.50	1.9500	1.1490	1.8720	1.0416
5.	C4	FRC-30-0.50	1.8800	1.1078	1.8890	0.9952
6.	C5	FRC-35-0.50	1.8000	1.0606	1.9020	0.9463

Table 7.3

Split Tensile Strength of San Fibre Reinforced Concrete (Fibre 0.75%)

S.N.	Test Series	Type of specimens	Split tensile strength N/mm^2	Split tensile strength ratio	Split tensile strength as per Equation 5.7 N/mm^2	Strength $\frac{\text{TEST}}{\text{THEORY}}$
1	2	3	4	5	6	7
1.	A	Plain concrete	1.6970	1.0000	1.6970	1.0000
2.	D1	FRC-15-0.75	1.9090	1.1249	1.8560	1.0285
3.	D2	FRC-20-0.75	1.9800	1.1667	1.9218	1.0302
4.	D3	FRC-25-0.75	2.0200	1.1903	1.9607	1.0302
5.	D4	FRC-30-0.75	1.9500	1.1490	1.9860	0.9818
6.	D5	FRC-35-0.75	1.8550	1.0930	2.0000	0.9275

Table 7.4

Split Tensile Strength of San Fibre Reinforced Concrete (Fibre 1.00%)

S.N.	Test Series	Type of specimens	Split tensile strength N/mm^2	Split tensile strength ratio	Split tensile strength as per Equation 5.7 N/mm^2	Strength TEST / THEORY
1	2	3	4	5	6	7
1.	A	Plain concrete	1.6970	1.0000	1.6970	1.0000
2.	E1	FRC-15-1.00	1.7240	1.0159	1.9100	0.9026
3.	E2	FRC-20-1.00	1.7800	1.0489	1.9970	0.8913
4.	E3	FRC-25-1.00	1.8150	1.0695	2.0490	0.8849
5.	E4	FRC-30-1.00	1.7550	1.0341	2.0830	0.8425
6.	E5	FRC-35-1.00	1.6800	0.9890	2.1080	0.7969

Table 7.5

Split Tensile Strength of San Fibre Reinforced Concrete (Fibre 1.25%)

S.N.	Test Series	Type of specimens	Split tensile strength N/mm^2	Split tensile strength ratio	Split tensile strength as per Equation 5.7 N/mm^2	Strength TEST / THEORY
1	2	3	4	5	6	7
1.	A	Plain concrete	1.6970	1.0000	1.6970	1.0000
2.	F1	FRC-15-1.25	1.6290	0.9599	1.9630	0.8290
3.	F2	FRC-20-1.25	1.7030	1.0030	2.0710	0.8223
4.	F3	FRC-25-1.25	1.7440	1.0276	2.1360	0.8164
5.	F4	FRC-30-1.25	1.6670	0.9821	2.1790	0.7650
6.	F5	FRC-35-1.25	1.5800	0.9310	2.2090	0.7152

Table 7.6

Split Tensile Strength of San Fibre Reinforced Concrete (Fibre 1.50%)

S.N.	Test Series	Type of specimens	Split tensile strength N/mm^2	Split tensile strength ratio	Split tensile strength as per Equation 5.7 N/mm^2	Strength TEST / THEORY
1	2	3	4	5	6	7
1.	A	Plain concrete	1.6970	1.0000	1.6970	1.0000
2.	G1	FRC-15-1.50	1.4400	0.8485	2.0170	0.7139
3.	G2	FRC-20-1.50	1.5250	0.8980	2.1460	0.7106
4.	G3	FRC-25-1.50	1.5760	0.9286	2.2240	0.7086
5.	G4	FRC-30-1.50	1.5050	0.8868	2.2760	0.6612
6.	G5	FRC-35-1.50	1.4030	0.8267	2.3130	0.6065

Table 7.7

Flexural Tensile Strength (Modulus of rupture) of San Fibre Reinforced Concrete

S.N.	Test Series	Type of specimens	Load at first crack N	First crack strength N/mm^2	First crack strength Ratio	Ultimate failure Load N
1	2	3	4	5	6	7
1	A	Plain concrete	8233.30	3.2930	1.0000	8233.30
2	B2	FRC-20-0.25	8400.00	3.3600	1.0212	8712.67
3	B3	FRC-25-0.25	8661.75	3.4647	1.0511	8835.36
4	B4	FRC-30-0.25	8600.00	3.4400	1.0455	8810.25
5	C2	FRC-20-0.50	8636.78	3.4547	1.0500	8994.00
6	C3	FRC-25-0.50	8934.66	3.5738	1.0862	9070.50
7	C4	FRC-30-0.50	8793.09	3.5182	1.0696	8887.25
8	D2	FRC-20-0.75	8934.13	3.5719	1.0856	9203.96
9	D3	FRC-25-0.75	9069.79	3.6279	1.1071	9288.00
10	D4	FRC-30-0.75	8865.44	3.5451	1.0775	8944.13

Table 7.7 (Continued)

Ultimate Cracking Strength N/mm^2	Ultimate Cracking Strength Ratio	Ultimate Crack St / First crack St (8/5)	Ultimate Cracking Strength as per Equation 5.7 N/mm^2	Ultimate Strength Test / Theory (8/11)
8	9	10	11	12
3.2930	1.0000	1.0000	3.2930	1.0000
3.4844	1.0590	1.0370	3.3641	1.0357
3.5341	1.0733	1.0211	3.3770	1.0465
3.5241	1.0701	1.0235	3.3857	1.0408
3.5976	1.0925	1.0404	3.4352	1.0472
3.6282	1.1018	1.0143	3.4611	1.0482
3.5565	1.0800	1.0097	3.4784	1.0224
3.6812	1.1179	1.0297	3.5063	1.0498
3.7152	1.1278	1.0186	3.5452	1.0479
3.5763	1.0860	1.0078	3.5712	1.0014

Table 7.8

Energy Absorption Capacity of San Fibre Reinforced Concrete

S.N.	Test Series	Type of specimens	Deflection mm	Energy Absorption Capacity N mm	Ratio of Energy Absorption Capacity
1	2	3	4	5	6
1	A	Plain concrete	0.0813	400.00	1.0000
2	B2	FRC-20-0.25	0.1550	637.40	1.5935
3	B3	FRC-25-0.25	0.1365	736.37	1.8409
4	B4	FRC-30-0.25	0.1300	650.78	1.6250
5	C2	FRC-20-0.50	0.1575	833.00	2.0825
6	C3	FRC-25-0.50	0.1625	956.00	2.3900
7	C4	FRC-30-0.50	0.1725	900.00	2.2500
8	D2	FRC-20-0.75	0.1750	950.00	2.3750
9	D3	FRC-25-0.75	0.2000	1200.0	3.0000
10	D4	FRC-30-0.75	0.2150	1235.3	3.0882

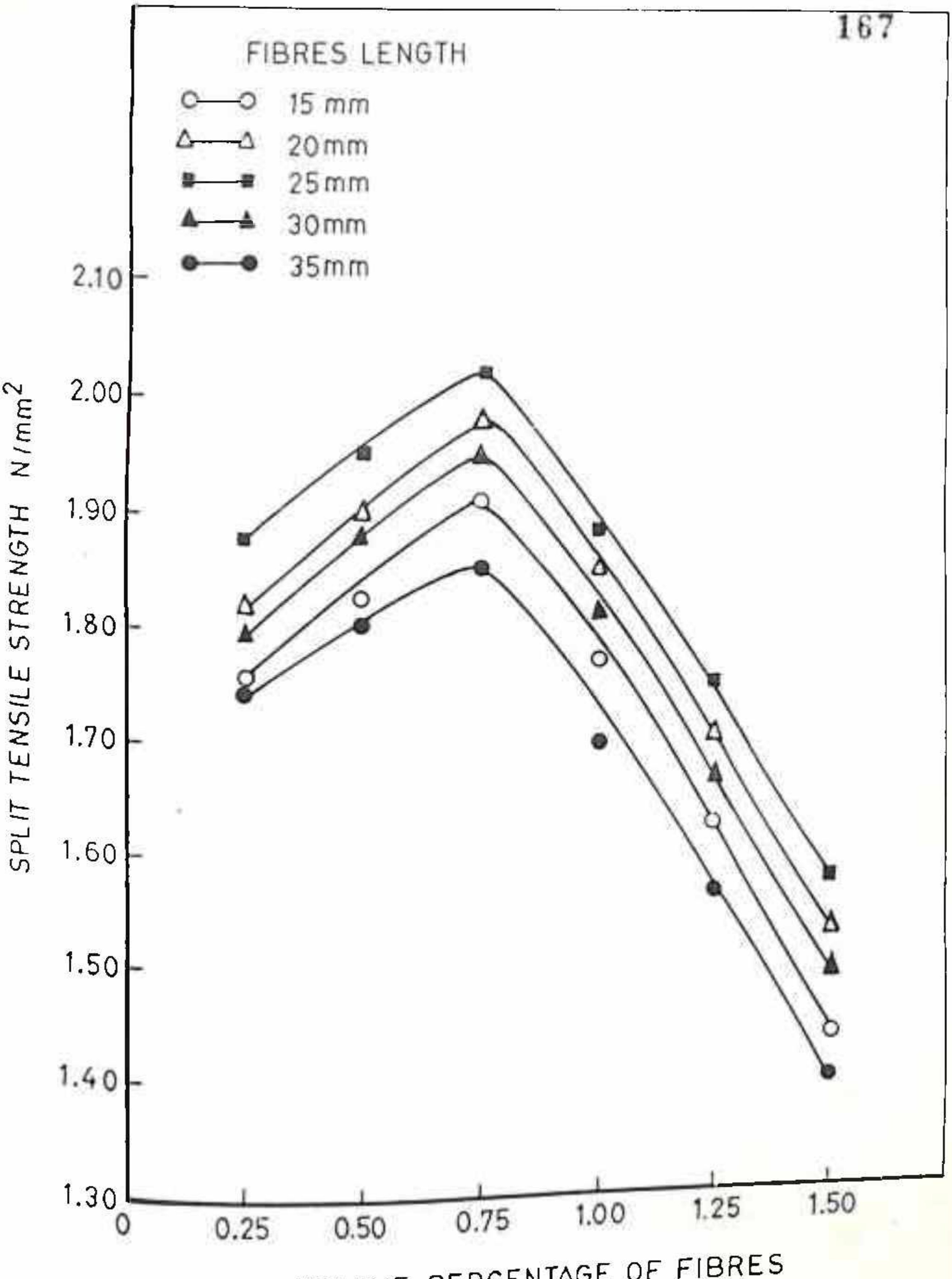


FIG. 7.1 EFFECT OF VOLUME PERCENTAGE OF FIBRES ON SPLIT TENSILE STRENGTH.

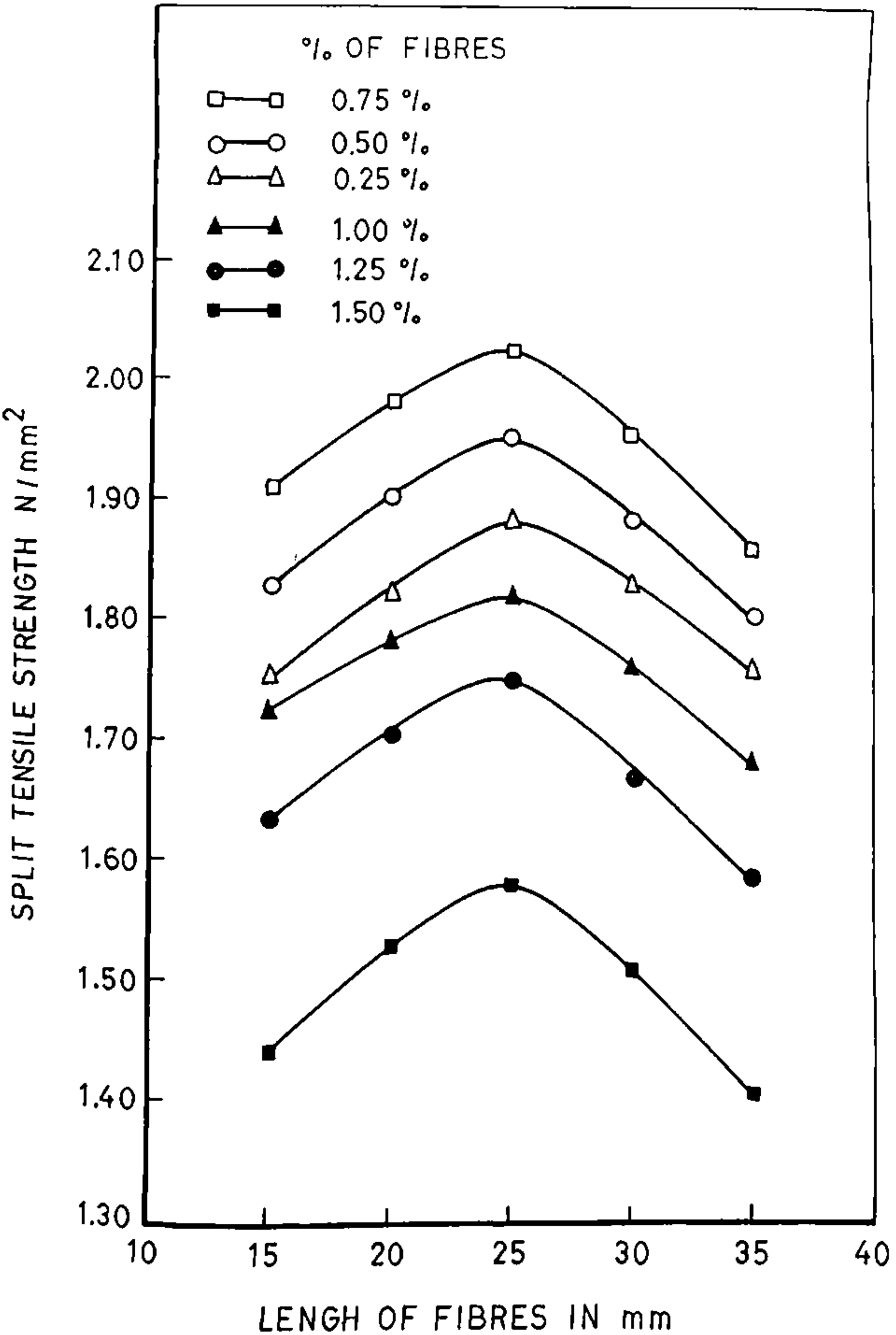


FIG.7.2 EFFECT OF LENGTH OF FIBRES ON SPLIT TENSILE STRENGTH

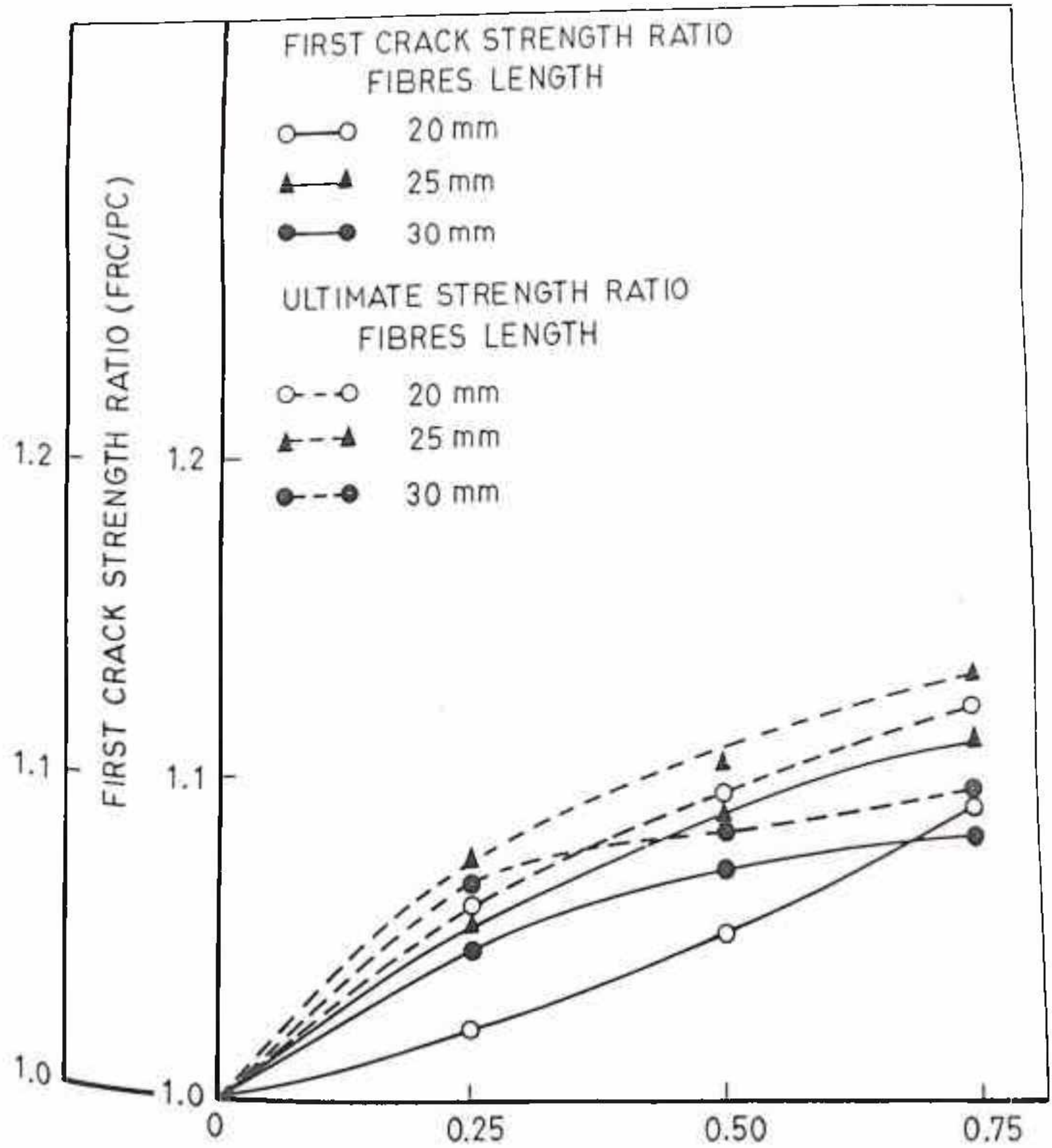


FIG.7.3 FIRST CRACK STRENGTH AND ULTIMATE STRENGTH RATIO Vs VOLUME PERCENTAGE OF FIBRES

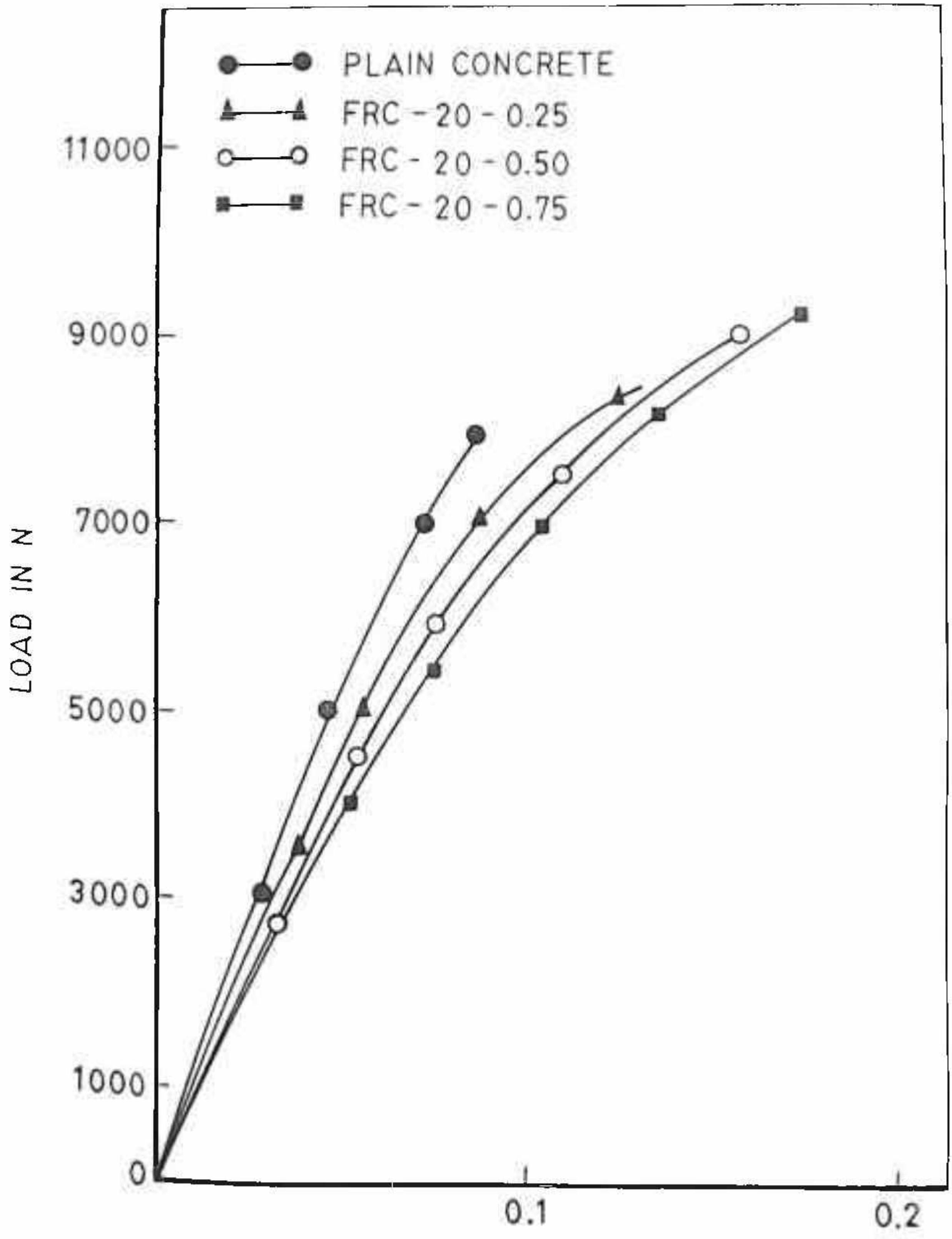


FIG.7.4 LOAD-DEFLECTION CURVES FOR BEAMS IN FLEXURAL TENSION

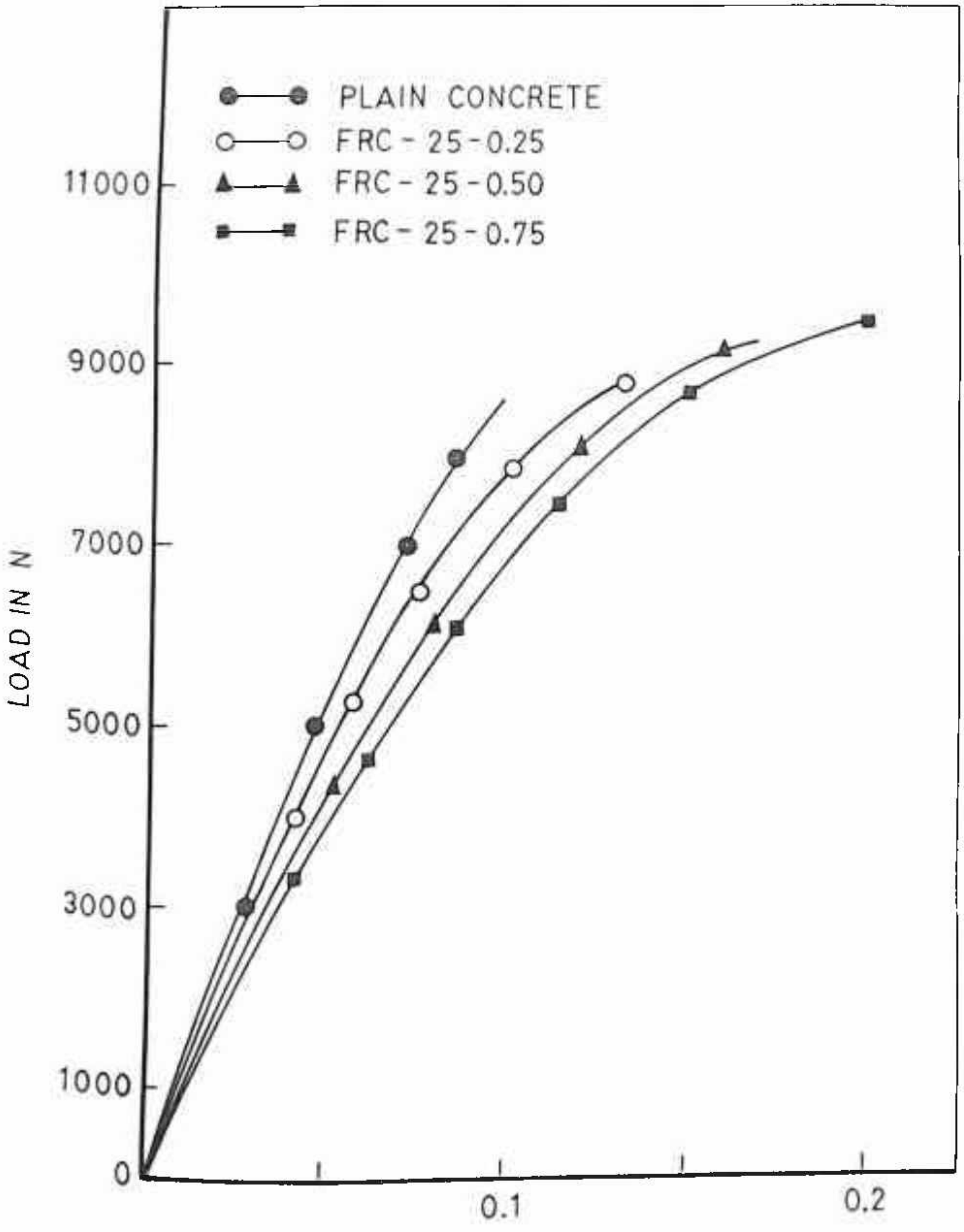


FIG.7.5 LOAD-DEFLECTION CURVES FOR BEAMS IN FLEXURAL TENSION

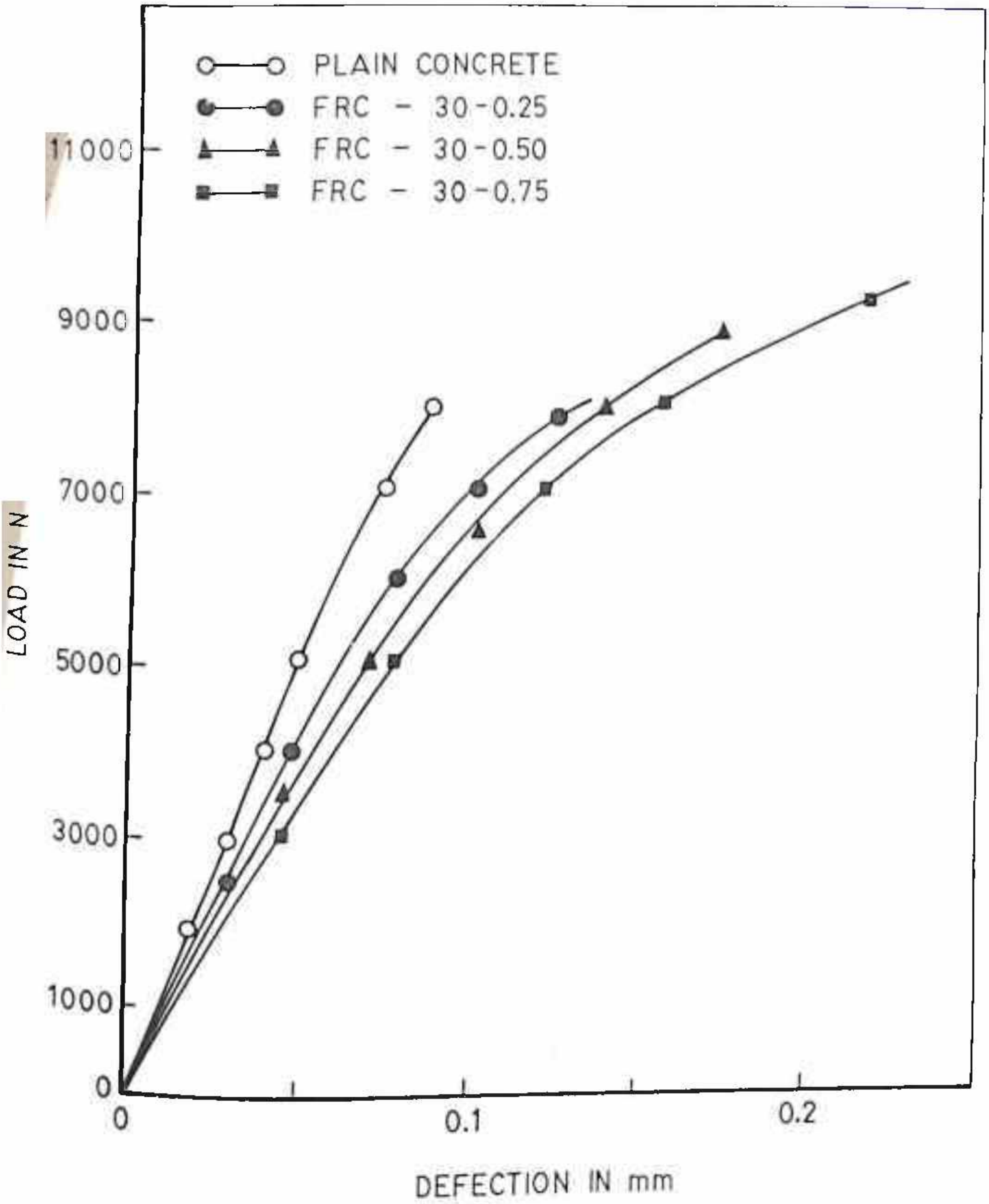


FIG.7.6 LOAD-DEFLECTION CURVES FOR BEAMS IN FLEXURAL TENSION

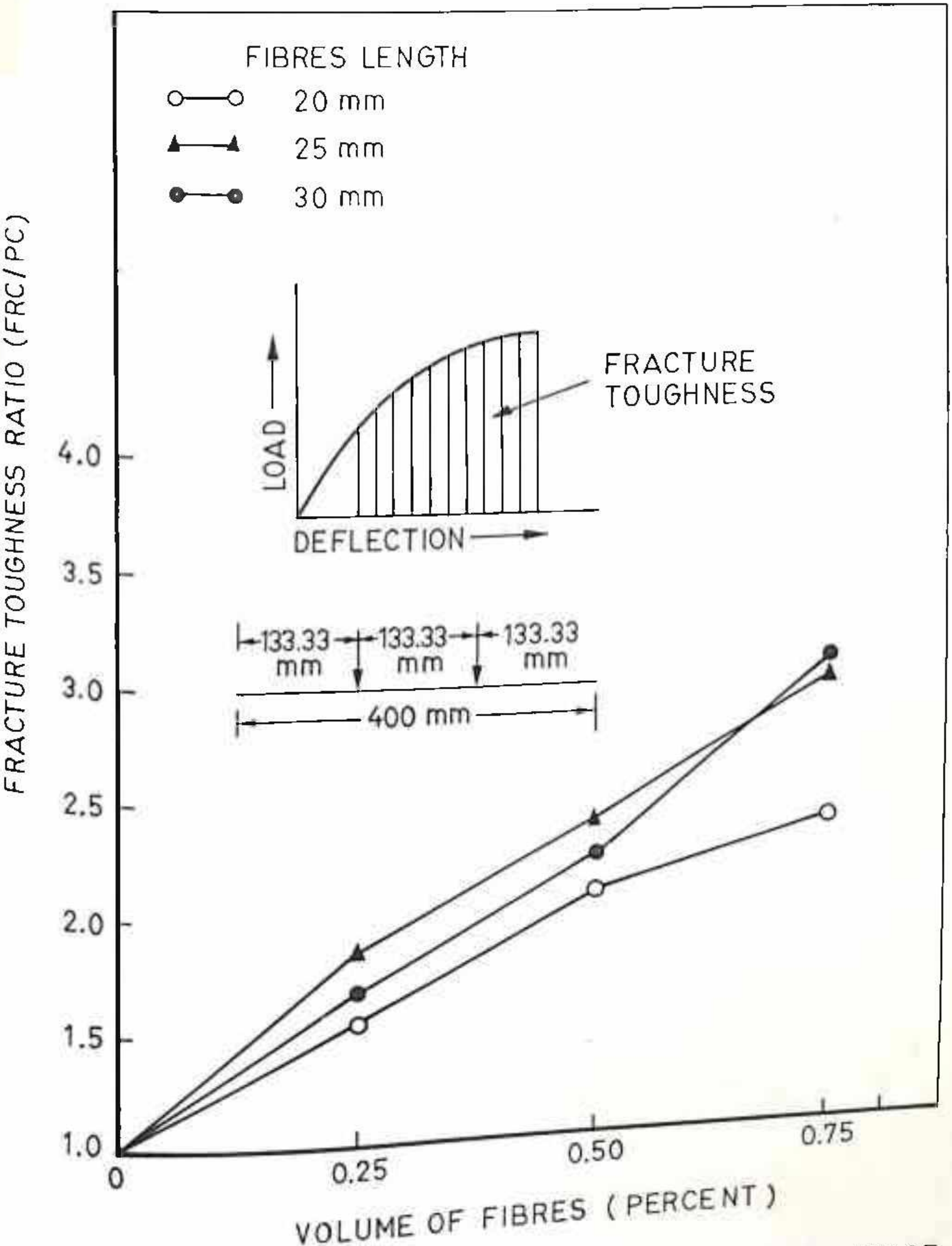


FIG.7.7 FRACTURE TOUGHNESS RATIO Vs VOLUME PERCENTAGE OF FIBRES IN FLEXURAL TENSION

PLATE 7.1 CRACK PATTERN OF PLAIN CONCRETE CYLINDER AFTER SPLIT TENSION.

PLATE 7.2 CRACK PATTERN OF SAN FIBRE RAINFORCED CONCRETE CYLINDERS AFTER SPLIT TENSION.

PLATE 7.3 CRACK PATTERN OF PLAIN CONCRETE BEAM AFTER FLEXURAL TENSION.

PLATE 7.4 CRACK PATTERN OF SAN FIBRE REINFORCED CONCRETE BEAM (FIBRE 0.25%) AFTER FLEXURAL TENSION.

PLATE 7.5 CRACK PATTERN OF SAN FIBRE REINFORCED CONCRETE BEAM (FIBRE 0.50%) AFTER FLEXURAL TENSION.

PLATE 7.6 CRACK PATTERN OF SAN FIBRE REINFORCED CONCRETE BEAM (FIBRE 0.75%) AFTER FLEXURAL TENSION.

CHAPTER VIII

STRENGTH OF FIBRE REINFORCED CONCRETE SHEETS

In Chapter 6 and Chapter 7, the effect of san fibre on various strength properties of concrete have been presented. In this chapter, similar effects in regard to cement concrete sheets under static and impact loading have been presented & discussed.

8.1 Static Strength Test

Plain and fibre reinforced cement concrete sheets of size 300 mm x 300 mm x 30 mm were used for the test. The sheets were subjected to static loading in a Universal testing machine. This test was performed on plain concrete sheets and sheets reinforced with fibres of optimum length viz. 25 mm and optimum percentage of fibre viz. 0.75%. by volume. Load deflection values are shown in table 8.1. Each value is the average of the values obtained from three specimens.

8.1.1 Discussion of Test Results

The load deflection curve (which is based on an average values from three specimens) of the fibre cement concrete sheets with 0.75% fibre content is presented in Figure 8.1. The load deflection curve shows two distinct slopes, linear up to a load of 2.8 KN and non-linear beyond this, and upto failure. This can be attributed to the formation of cracks and slippage of fibres.

It may be noted that the load carrying capacity of the reinforced concrete sheets improved by 15% to 20% over plain concrete sheets.

Plain concrete sheets failed suddenly without giving any warning (due to this deflection could not be recorded accurately). Introduction of fibres in the concrete increases ductility considerably and the sheets fail due to fibres slipping out of position, crack forms along the center line parallel to the supporting edges. A close examination of the fractured FRC sheets show that the cracks width is more at the center of the sheets and it decreases towards the edges, there by indicating bond failure.

8.2 Impact Strength Test

Impact strength tests were carried out by the Falling Weight method, which was used to determine the comparative impact resistance of the plain and fibre reinforced cement concrete sheets. In this test a metallic piece of weight 69.0 N (test set up shown in fig. 3.1) was allowed to fall freely so that the impact occurred at the center of the sheets. The height through which the weight fell when the sheet got fractured was noted. Impact strength was taken to be proportional to the height from which the weight had to be dropped on the sheets to cause failure. This test was performed for plain concrete sheets and sheets reinforced with San fibres of optimum length viz. 25 mm mixed with cement concrete in there different proportions viz. 0.25%, 0.50%, and 0.75%. Table 8.2 presents the impact strength results. Plate 8.1 shows the crack pattern of plain concrete sheet, and plates 8.2 to 8.4 show crack pattern of san fibres reinforced concrete sheets.

8.2.1 Discussion of Test Results

Impact strength results of plain and fibre reinforced concrete sheets have been presented in table 8.2. Fig 8.2 shows the plot between impact strength ratio and percentage of fibres. It is clear that presence of San fibres increases the impact strength of the plain cement concrete sheets by 11.5%, 18.44% and 26.34% respectively for 0.25%, 0.50% and 0.75% fibres in cement concrete by volume.

The important observation, which was made during the impact strength test was in regard to the mode of failure. In case of plain cement concrete sheets failed suddenly where as in case of FRC sheets failure was not sudden, because of fibres being pulled out of position with little tensile force caused by the impact. However, the fracture occurred along the center line in both cases.

Table 8.1

Load-Deflection Values for Concrete Sheets Reinforced with San Fibre of Length 25mm and 0.75% by Volume

Load in KN	Deflection In mm
0.20	0.024
0.40	0.048
0.60	0.070
0.80	0.090
1.00	0.106
1.20	0.136
1.40	0.156
1.60	0.182
1.80	0.202
2.00	0.224
2.20	0.250
2.40	0.274
2.60	0.292
2.80	0.312
3.00	0.342
3.20	0.368
3.40	0.400
3.60	0.430
3.80	0.446
4.00	0.462
4.20	0.510

Table 8.2

Impact Strength of San Fibre Reinforced Concrete Sheets

S.N.	Test Series	Types of specimens	Average Height of Fall in meter	Impact Strength in KN-m	%Improvement Over plain Concrete
1	SA	Plain Concrete	0.3166	0.02184	-
2.	SB3	FRC-25-0.25	0.3533	0.02437	11.59
3.	SC3	FRC-25-0.50	0.3750	0.02558	18.44
4.	SD3	FRC-25-0.75	0.4000	0.27600	26.34

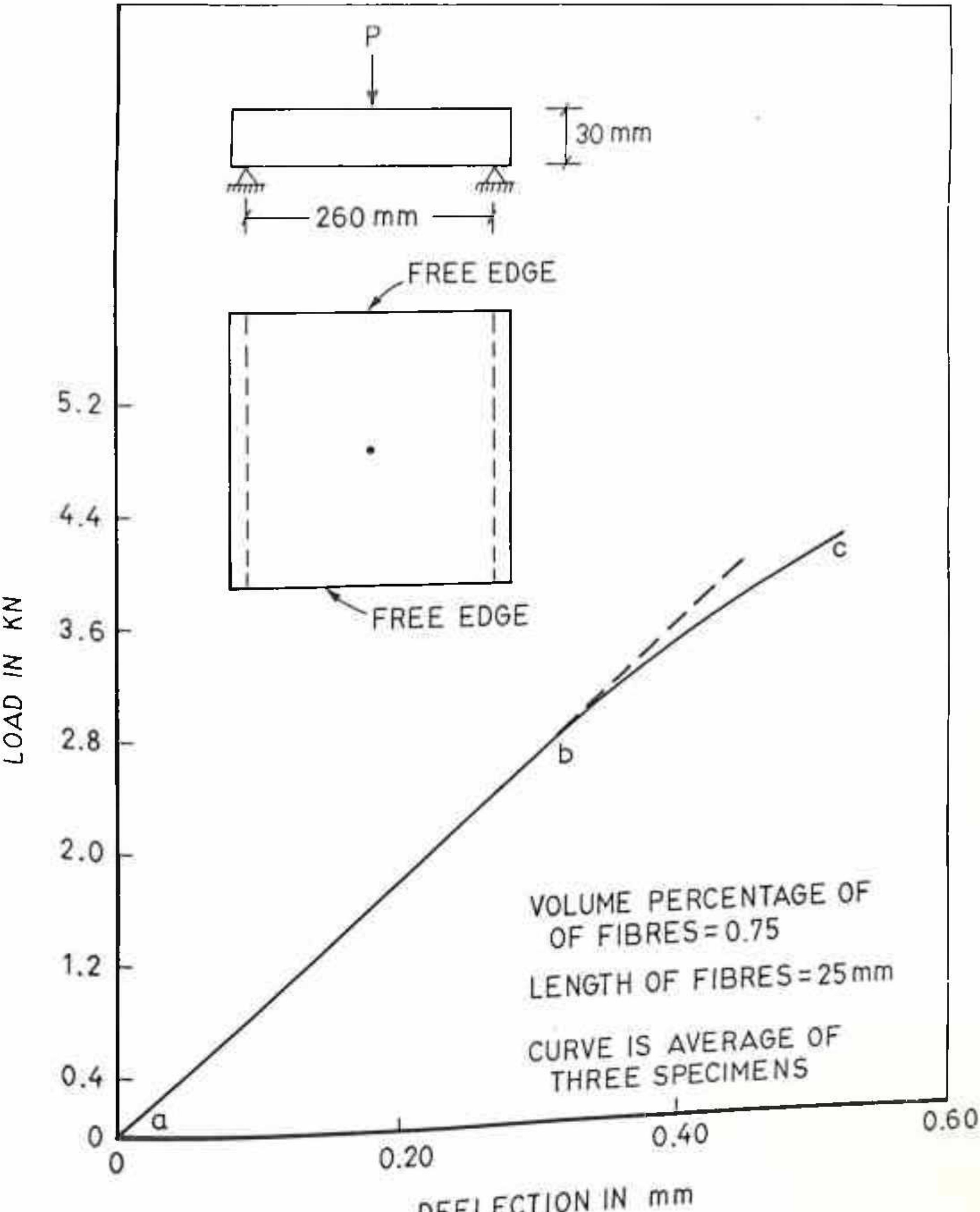


FIG. 8.1 LOAD-DEFLECTION CURVE OF SAN FIBRE REINFORCED CONCRETE SHEET

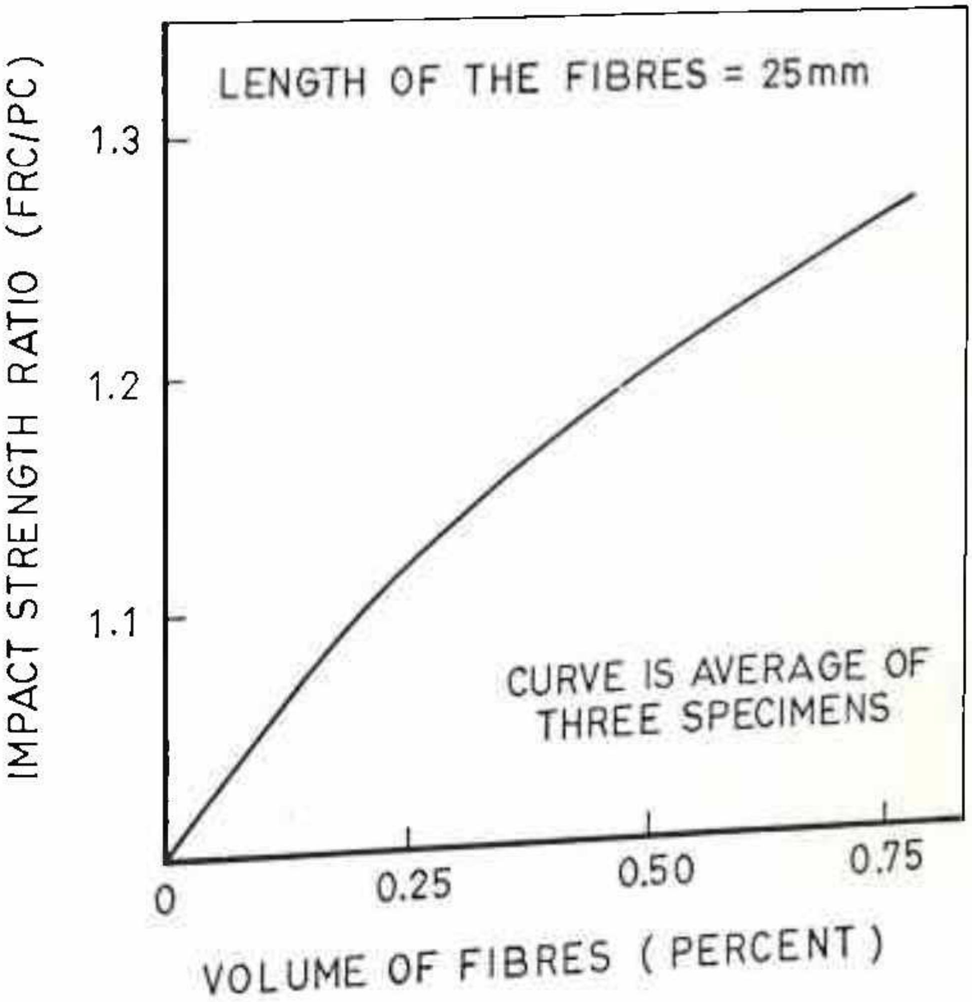
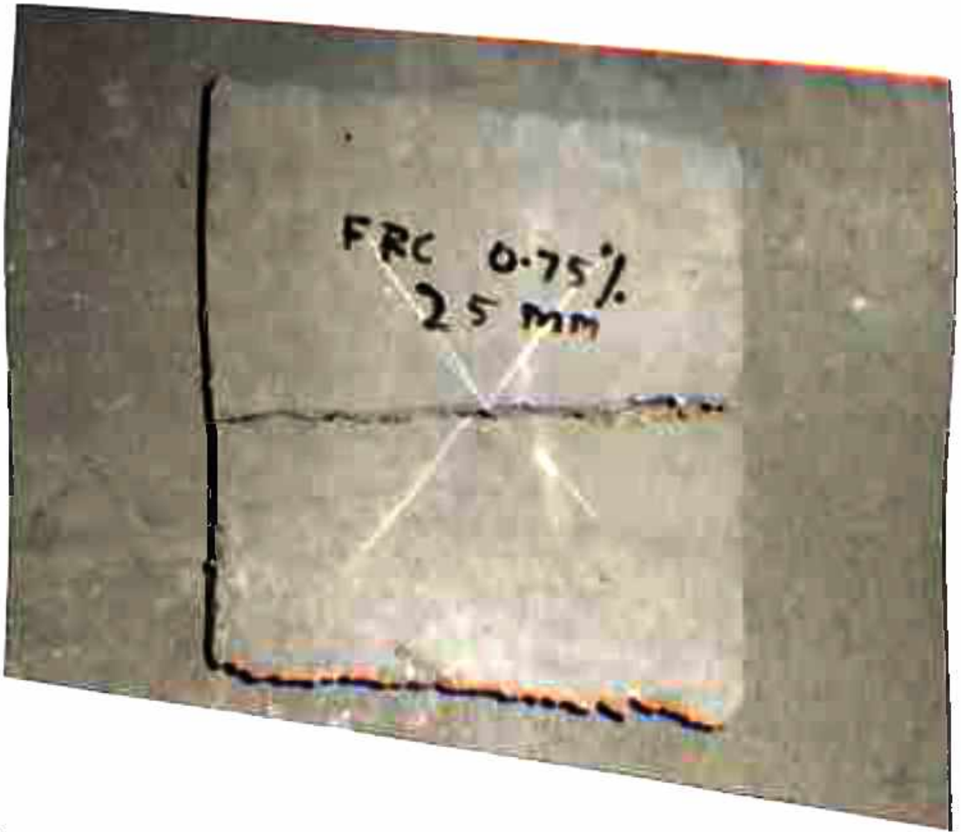


FIG. 8.2 IMPACT STRENGTH RATIO Vs VOLUME PERCENTAGE OF FIBRES.

PLATE 8.1 CRACK PATTERN OF PLAIN CONCRERE SHEET AFTER IMPACT FAILURE.

PLATE 8.2 CRACK PATTERN OF SAN FIBRE REINFORCED CONCRETE SHEET (FIBRE 0.25%) AFTER IMPACT FAILURE.

PLATE 8.3 CRACK PATTERN OF SAN FIBRE REINFORCED CONCRETE SHEET (FIBRE 0.50%) AFTER IMPACT FAILURE.



PLATE

CHAPTER IX

FLEXURAL BEHAVIOUR OF REINFORCED CONCRETE BEAMS

In this chapter behaviour of conventionally reinforced concrete beams further reinforced with fibres, and plain concrete beams reinforced with twines (made of fibres) have been presented.

9.1 Flexural Behaviour of Conventionally Reinforced Fibre Concrete Beams

The test results in respect of the conventionally reinforced fibre concrete beams have been presented in tables 9.1 to 9.8 and figures 9.1 to 9.14.

9.1.1 Strain in Tension Steel

The strain in the conventional tensile reinforcement was measured by a mechanical gauge (whittmore gauge) with the help of steel studs welded to the bars at the central section. The length of the studs was kept equal to the thickness of side cover to the tensile reinforcement so that after casting the beam, the gauge points appeared on the surface. The measured values of the strains for under reinforced and over reinforced beams are listed in the column 4 of table 9.1 and 9.5 respectively.

9.1.2 Strain in Concrete

The strains in the concrete were measured at the central section along the depth of the beams. The maximum strains developed in the extreme compression layer of the beams are listed in column 4 of the tables 9.4 and 9.8.

(a) Under-Reinforced Beams

The average flexural strain values in the extreme compression layer indicate that the average penultimate strain in conventionally reinforced concrete beams was equal to 0.3200 percent. The strains in the reinforced fibre concrete beams exceeded the strains in the conventionally reinforced concrete without fibres by 39.06% to 66.56% depending on the volume percentage of the fibres. The maximum increase of 66.56% was obtained in beams having fibre volume percentage of 0.75.

Profiles of strain distribution along the depth at central section of the reinforced concrete beams and reinforced fibre concrete beams at various loading stages are shown in figures 9.3 to 9.6. The strain distribution along the depth is linear for almost all the stages of loading.

(b) Over-Reinforced Beams

The average values of measured penultimate flexural compressive strains in extreme compressive layer of the over reinforced concrete beams was 0.3950 percent. The strains in the reinforced fibre concrete beams increases from 75.94% to 134.32 percent depending upon the volume percentage of fibres. The maximum increase of 134.32% was obtained in the beams having fibre volume percentage of 0.75.

Strain distribution at central section of the reinforced concrete beams and reinforced fibre concrete beams at various loading stages are shown in figures 9.7 to 9.10.

9.1.3 Cracking And Ultimate Load

(a) Under-Reinforced Beams

The load at first crack was determined by visual inspection. For all the beams marginal increase in the first cracking load was observed. The maximum increase of 9.60% was obtained for beams with fibre volume percentage of 0.75. The first cracking loads and their ratios are listed in columns 4 and 5 of table 9.2.

Similarly, the ultimate failure loads and their ratios are given in the columns 6 and 7 of the table 9.2. The maximum increase of 11.56% was obtained for beams with fibre volume percentage of 0.75.

(b) Over-Reinforced Beams

All the reinforced fibre concrete beams showed only marginal increase in first cracking load over reinforced concrete beams. The maximum increase of 3.84% was for beams with fibre volume percentage of 0.75. The first cracking load and their ratios are listed in columns 4 and 5 of the table 9.6. Ultimate failure loads and their ratios are given in columns 6 and 7 of the table 9.6. The maximum increase of 5.14% was for beams with fibre volume percentage of 0.75.

Under-reinforced fibre concrete beams have higher increase at first cracking load than that of over-reinforced fibre concrete beams. Similar is the case with ultimate failure load.

9.1.4 Cracking And Ultimate Moment

(a) Under-Reinforced Beams

The moments at first cracking and their ratio are listed in the columns 4 and 5 of the table 9.3. The maximum increase of 9.6% was obtained for fibre volume percentage of 0.75.

Ultimate moments and their ratios are listed in columns 6 and 7 of table 9.3. The maximum increase of 11.56% was for beams with fibre volume percentage of 0.75. The first crack and ultimate moment ratio Vs. volume percentage of fibres have been plotted in fig. 9.1 and 9.2.

(b) Over-Reinforced Beams

Ultimate moment and their ratios are given in columns 4 and 5 of table 9.7. Maximum increase of 5.14% was for fibre volume percentage of 0.75. The first crack and ultimate moment ratio Vs. volume percentage of fibre has been plotted shown in fig 9.1. and 9.2.

9.1.5 Curvature

(a) Under-Reinforced Beams

The ultimate curvatures and their ratios are listed in columns 6 and 7 of table 9.4. Curvature increases with increase in the percentage of fibres. The maximum increase in curvature in reinforced fibre concrete beams is 77.68% over reinforced concrete beams.

(b) Over-Reinforced Beams

The ultimate curvatures and their ratios are presented in the columns 6 and 7 of table 9.8.

The maximum increase in curvature in reinforced fibre concrete beams is 129.55% over reinforced concrete beams.

9.1.6 Moment Curvature Relationships

(a) Under-Reinforced Beams

The experimental moment curvature plots have been presented in figure 9.11.

It is clear from the fig 9.11 that even though the difference in the maximum moment carried by the reinforced concrete beams and that by the reinforced fibre concrete beams differed little, reinforced fibre concrete beams exhibited considerably higher curvatures compared to reinforced concrete beams. This could be due to the fact that in order to mobilize the same amount of compressive force in the concrete, the maximum strain of the fibre concrete would be higher because of the greater ductility of this material.

(b) Over-Reinforced Beams

The experimental moment-curvature plots have been presented in fig. 9.12.

Moment-curvature relationships of reinforced fibre concrete beams over reinforced concrete beams shows a marked difference. Such a large difference in the curvature will only be possible if the extreme compression fibre strains are large, which is possible because of the high ductile nature of material. The large curvature changes in the over-reinforced fibre concrete beams lead to the conclusion that addition of natural fibres will be advantageous.

9.1.7 Deflections

(a) Under-Reinforced Beams

Load-deflection plots for reinforced concrete beams and reinforced fibre concrete beams have been shown in fig. 9.13.

Upto first crack load, the plots are linear for all the beams. After the first crack it takes the shape of a curve. It was observed that though the deflections at last loading stages were not very large, the beams continued to deflect thus giving ample warning before collapse.

(b) Over-Reinforced Beams

Load-deflection plots of reinforced concrete beams and reinforced fibre concrete beams have been shown in fig 9.14.

Upto fist crack the plots are linear and after-wards take the shape of a curve. The reinforced fibre concrete beams continued to deflect before complete failure. The deflections at ultimate failure are smaller in over reinforced beams as compared to under reinforced beams.

9.1.8 Cracking Characteristics

(a) Under-Reinforced Beams

Reinforced fibre concrete beams showed smaller crack widths compared to reinforced concrete beams. It was also observed that there was marginal decrease in crack width as the percentage of fibres was increased. The number of cracks in almost all the reinforced fibre concrete beams increased as compared to reinforced concrete beams without fibres.

Number of cracks in the reinforced concrete beams with out fibres varied between 11-13. The average spacing between the cracks varied from 60 to 70 mm.

Number of cracks in the reinforced fibre concrete beams varied between 11-16. The average spacing between the cracks varied from 55 to 67 mm.

(b) Over-Reinforced Beams

All the reinforced fibre concrete beams had more number of cracks as compared to reinforced concrete beams with out fibres. Average crack spacing in all the reinforced fibre concrete beams was smaller to that of reinforced concrete beams without fibres.

Number of cracks in the reinforced concrete beams with out fibres varied between 13-16. The average spacing between the cracks varied from 56 to 62 mm. Number of cracks in the reinforced fibre concrete beams varied between 15-19. The average spacing between the cracks varied from 42 to 54 mm.

9.2 Flexural Behaviour of Concrete Beams reinforced with Twines

9.2.1 Tensile Properties of Twines

Twines of several diameters were made from natural San fibres. These twines were tested first for their tensile strength. The test results in respect of twines of various diameters have been presented in table 9.9. The stress-strain curves for the twines are shown in figure 9.15.

9.2.2 Concrete Beams Reinforced with Twines

For the present investigation, it was decided to use twines of 2.95 mm diameter because twines of this diameter are commercially available.

Three series of concrete beams were cast with three different percentage of twines (0.7512 %, 0.5467% and 0.4100%) of the cross-sectional area of the beam, and another three series of concrete beams were cast with the three different percentage of the twines along with 0.75% of fibers of length 25 mm. On an average three specimens was tested and the results ~~are~~ were the average of 3 specimens.

The six series of the beams are designated as mentioned below:

Test Series	Types of Concrete Beams	
	% of Twines	% of Fibres
AT1	0.7512	-
AT2	0.5467	-
AT3	0.4100	-
D3T1	0.7512	0.75
D3T2	0.5467	0.75
D3T3	0.4100	0.75

All the beams were tested on a 50 ton universal testing machine. The loads and the corresponding deflections were observed at every 1000 N interval for increasing loads until failure.

The load-deflection curves for concrete beams reinforced with twines and concrete beams reinforced with twines and fibres are presented in fig 9.16 and fig 9.17 respectively.

For the loaded specimens the occurrence of cracks is usually sudden for the beams reinforced with twines only. Before the occurrence of the first crack, the load-deflection curve is linear with a relatively steep slope corresponding to the high flexural stiffness (EI) of the uncracked element. The appearance of the first wide crack greatly reduces the average flexural stiffness. As the crack grows further, the average flexural stiffness reduces further. The twines in the open crack and those in close vicinity of it gain strength through increased local strains. Then the load-deflection curves start rising again though gradually.

A point is reached at which the resistance offered by the twines at the critical section exceeds that offered in a potential second crack region and thus a second crack occurs followed by another drop in the load-deflection curve.

The strength capacity of the beam is governed by those of the critical sections. It therefore, varies depending on which stage of the load-deflection curve of the beam has been reached. Right from the incipience of a crack, the strength capacity is governed by the critical section and section of potential crack. It has been observed that the strength capacity before occurrence of first crack is slightly higher than that of corresponding plain concrete specimens (Fig 9.16). The increase in strength capacity between the occurrence of the first crack to failure is about 15% to 25% of the maximum precracked strength.

Similarly, in case of beams reinforced twines and fibres, the increase in strength capacity between the occurrence of first crack and failure is about 18% to 32% of the maximum precracked strength.

Table 9.1

STRAIN IN FLEXURAL STEEL (UNDER REINFORCED BEAMS)

S.N.	Beam Series	Beam Type	Strain at Central Section measured by mechanical strain gauge $\times 10^{-6}$
1	2	3	4
1.	AU	Reinforced Concrete	2002.7900
2.	B3U	RFC-25-0.25	1960.0000
3.	C3U	RFC-25-0.50	1940.3400
4.	D3U	RFC-25-0.75	1890.5600

Table 9.2

CRACKING AND FAILURE LOAD (UNDER REINFORCED BEAMS)

S.N.	Beam Series	Beam Type	Load at First crack KN	Ratio of Load at first crack	Load at ultimate failure KN	Ratio of load at ultimate Failure
1	2	3	4	5	6	7
1.	AU	Reinforced Concrete	12.5060	1.0000	32.0000	1.0000
2.	B3U	RFC-25-0.25	12.9500	1.0360	33.4000	1.0437
3.	C3U	RFC-25-0.50	13.2000	1.0560	34.8000	1.0875
4.	D3U	RFC-25-0.75	13.7000	1.0960	35.7000	1.1156

Table 9.3

MOMENT AT FIRST CRACK AND AT FAILURE(UNDER REINFORCED BEAMS)

S.N.	Beam Series	Beam Type	Moment at First crack KN-m	Ratio of Moment at first crack	Moment at failure KN-m	Ratio of moment at failure
1	2	3	4	5	6	7
1.	AU	Reinforced Concrete	2.2500	1.0000	5.7600	1.0000
2.	B3U	RFC-25-0.25	2.3310	1.0360	6.0120	1.0437
3.	C3U	RFC-25-0.50	2.3760	1.0560	6.2640	1.0875
4.	D3U	RFC-25-0.75	2.4660	1.0960	6.4260	1.1156

Table 9.4

STRAINS AND CURVATURE AT CENTRAL SECTION

(UNDER REINFORCED BEAMS)

S.N.	Beam Series	Beam Type	Strain (Percent)	Strain Ratio	Curvature $x\ 10^{-5}$	Curvature Ratio
1	2	3	4	5	6	7
1.	AU	Reinforced Concrete	0.3200	1.0000	6.5615	1.0000
2.	B3U	RFC-25-0.25	0.4450	1.3906	8.9386	1.3622
3.	C3U	RFC-25-0.50	0.4690	1.4656	10.0350	1.5293
4.	D3U	RFC-25-0.75	0.5330	1.6656	11.6589	1.7768

Table 9.5

STRAIN IN FLEXURAL STEEL (OVER REINFORCED BEAMS)

S.N.	Beam Series	Beam Type	Strain at Central Section measured by mechanical strain gauge $\times 10^{-6}$
1	2	3	4
1.	AO	Reinforced Concrete	1420.6500
2.	B30	RFC-25-0.25	1703.6200
3.	C30	RFC-25-0.50	1750.6900
4.	D30	RFC-25-0.75	1733.5600

Table 9.6

CRACKING AND FAILURE LOAD (OVER REINFORCED BEAMS)

S.N.	Beam Series	Beam Type	Load at First crack KN	Ratio of Load at first crack	Load at ultimate failure KN	Ratio of load at ultimate Failure
1	2	3	4	5	6	7
1.	AO	Reinforced Concrete	26.0000	1.0000	70.0000	1.0000
2.	B30	RFC-25-0.25	26.4000	1.0153	71.6000	1.0228
3.	C30	RFC-25-0.50	26.7000	1.0269	72.8000	1.0400
4.	D30	RFC-25-0.75	27.0000	1.0384	73.6000	1.0514

Table 9.7

MOMENT AT FIRST CRACK AND AT FAILURE (OVER REINFORCED BEAMS)

S.N.	Beam Series	Beam Type	Moment at First crack KN-m	Ratio of Moment at first crack	Moment at failure KN-m	Ratio of moment at failure
1	2	3	4	5	6	7
1.	AO	Reinforced Concrete	4.6800	1.0000	12.6000	1.0000
2.	B30	RFC-25-0.25	4.7520	1.0153	12.8800	1.0228
3.	C30	RFC-25-0.50	4.8060	1.0269	13.1040	1.0400
4.	D30	RFC-25-0.75	4.8600	1.0384	13.2480	1.0514

Table 9.8

STRAINS AND CURVATURE AT CENTRAL SECTION (OVER REINFORCED BEAMS)

S.N.	Beam Series	Beam Type	Strain (Percent)	Strain Ratio	Curvature $x\ 10^{-5}$	Curvature Ratio
1	2	3	4	5	6	7
1.	AO	Reinforced Concrete	0.3950	1.0000	4.0497	1.0000
2.	B30	RFC-25-0.25	0.6950	1.7594	7.1255	1.7595
3.	C30	RFC-25-0.50	0.8200	2.0759	8.4071	2.0759
4.	D30	RFC-25-0.75	0.9256	2.3432	9.2961	2.2955

Table 9.9

STRENGTH PROPERTIES OF TWINES

S.N.	Diameter of Twines mm	Ultimate Tensile Strength N/mm^2	Ultimate Strain percent
1	2	3	4
1.	0.06 (Single fibre)	220.00	1.29 - 1.34
2.	1.00	142.69	2.02 2.12
3.	1.90	120.32	2.66 - 2.82
4.	2.95	101.89	3.34 - 3.52
5.	3.65	89.65	3.72 - 3.83

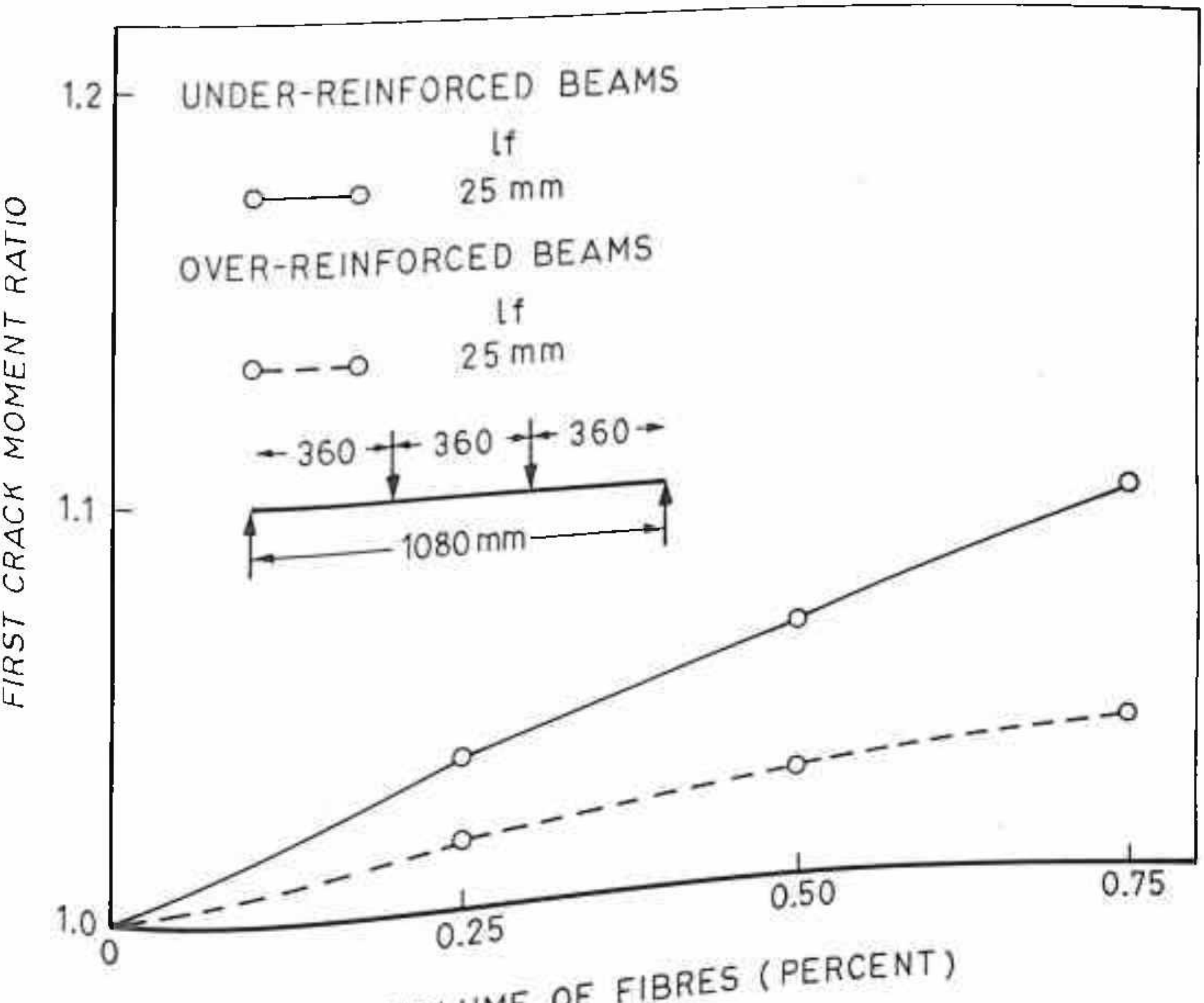


FIG.9.1 EFFECT OF VOLUME PERCENTAGE OF FIBRES ON FIRST CRACK MOMENT RATIO OF CONVENTIONALLY REINFORCED CONCRETE BEAMS

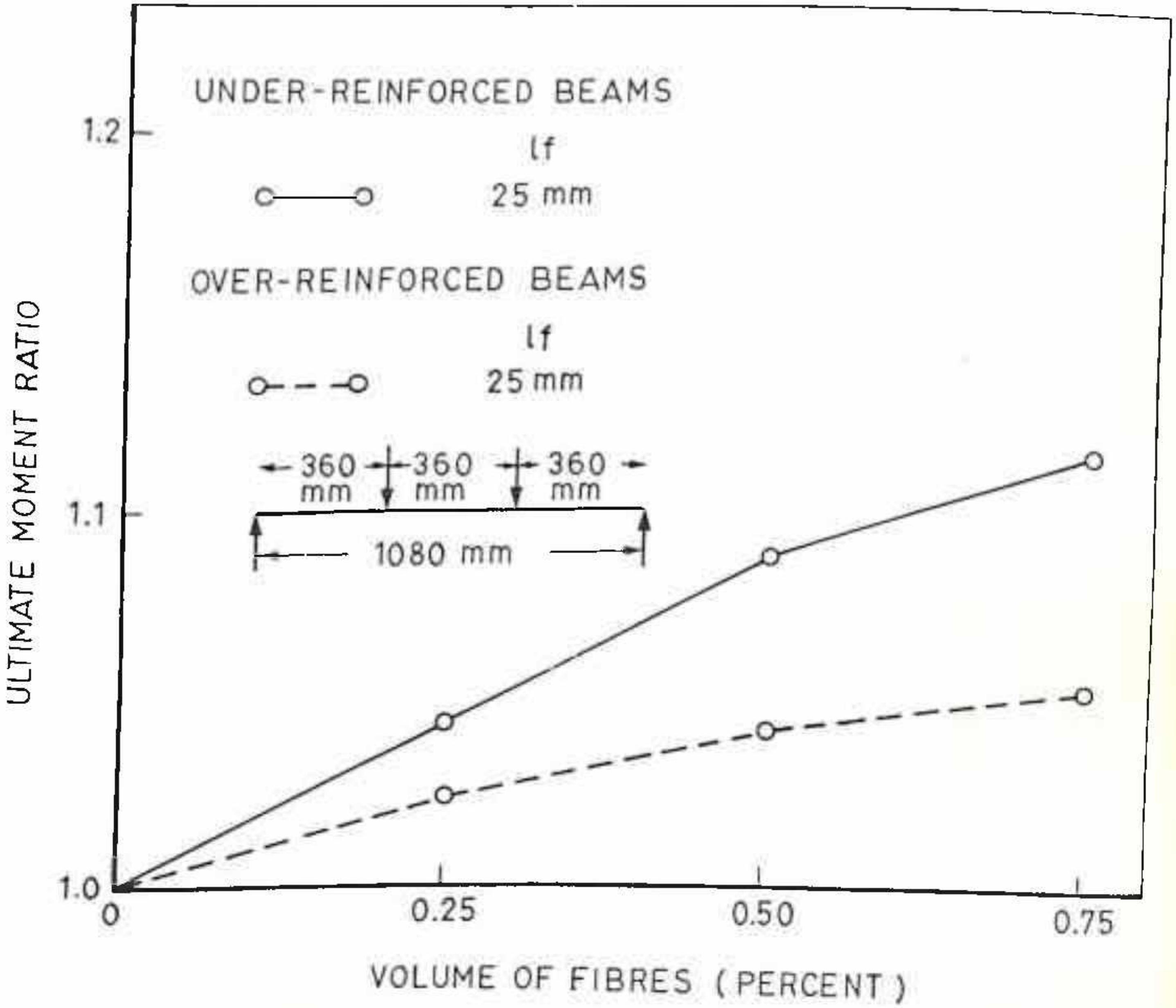


FIG. 9.2 EFFECT OF VOLUME PERCENTAGE ON ULTIMATE MOMENT RATIO OF CONVENTIONALLY REINFORCED CONCRETE BEAMS

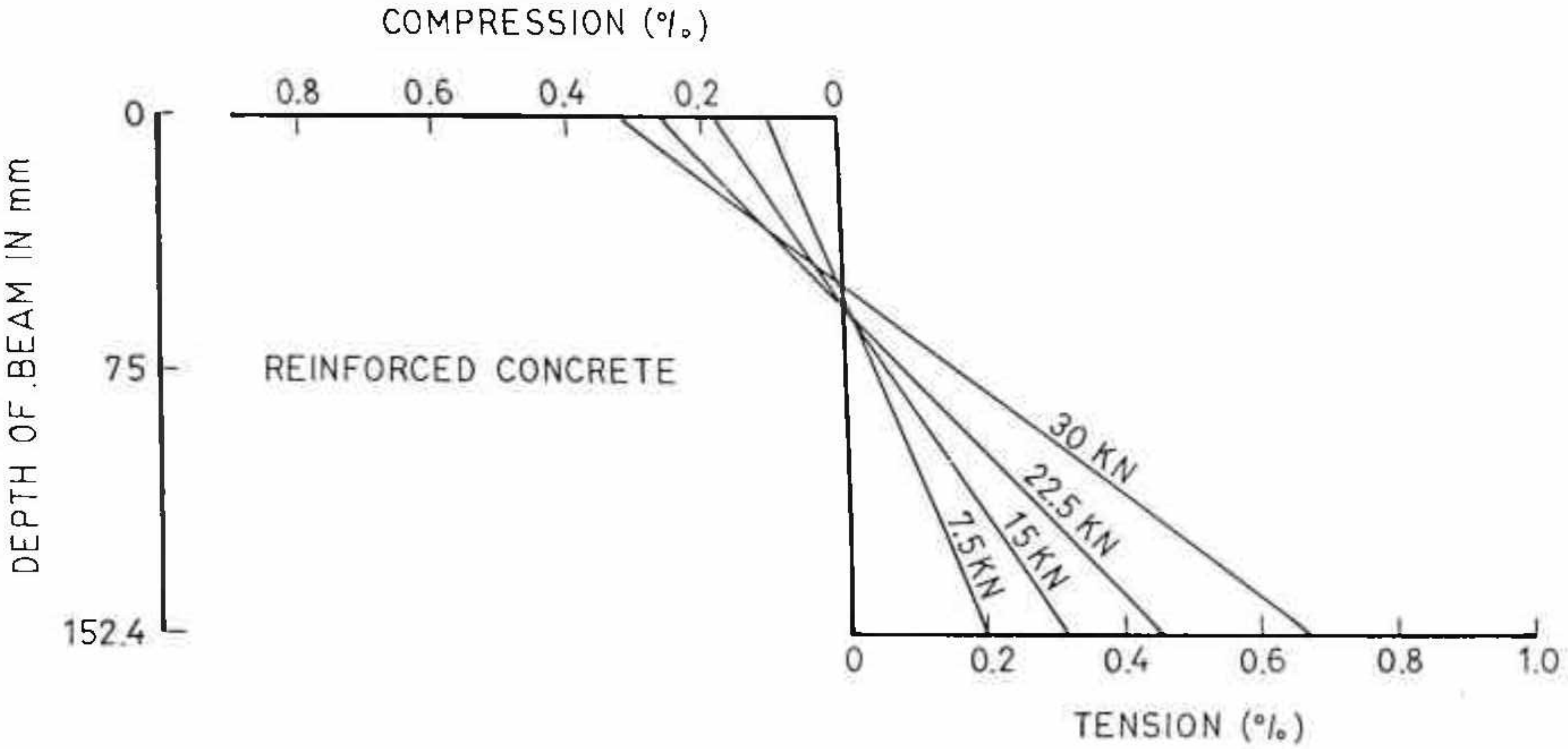


FIG.9.3 STRAIN DISTRIBUTION OF UNDER-REINFORCED CONCRETE BEAMS AT CENTRAL SECTION

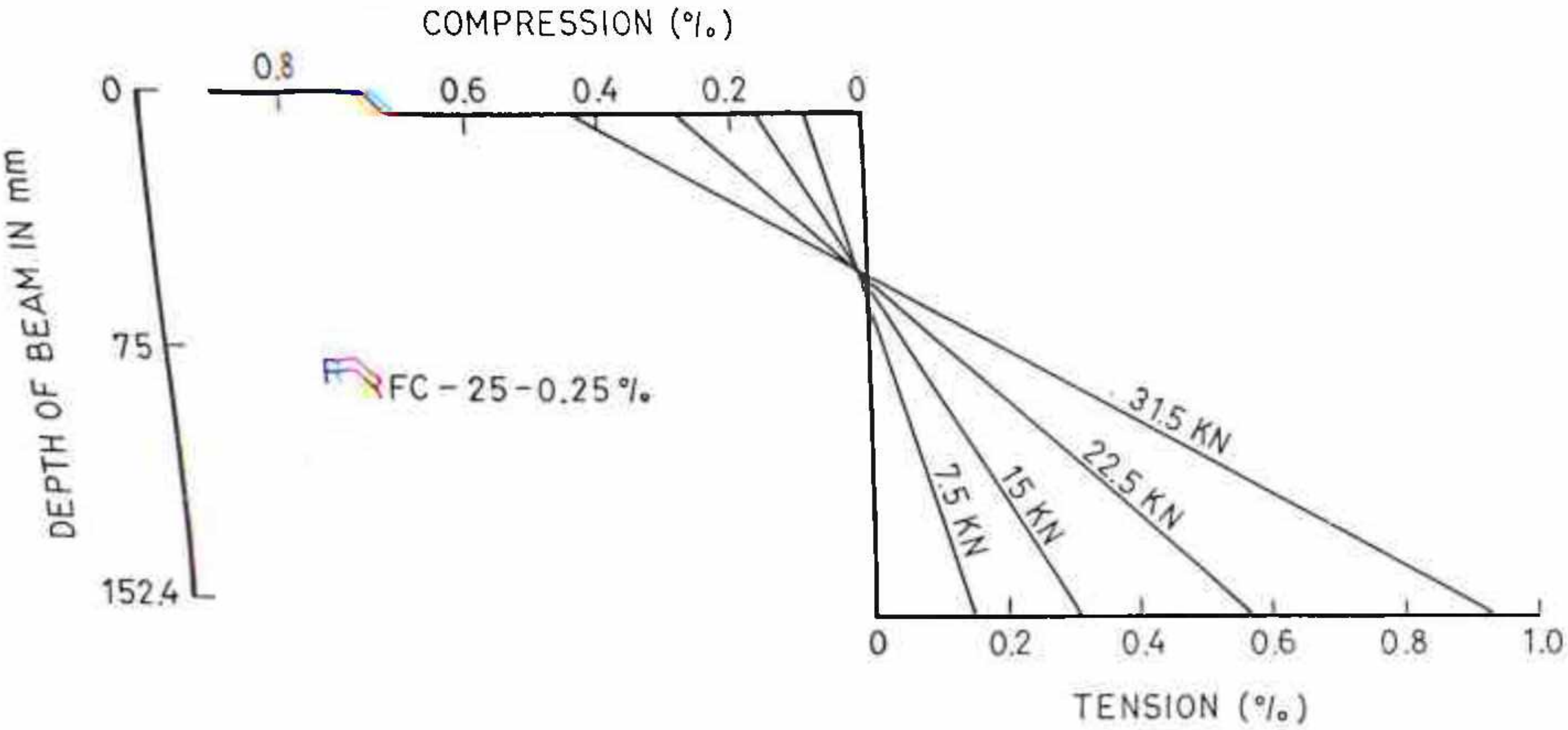


FIG.9.4 STRAIN DISTRIBUTION OF UNDER-REINFORCED FIBRE CONCRETE BEAMS AT CENTRAL SECTION

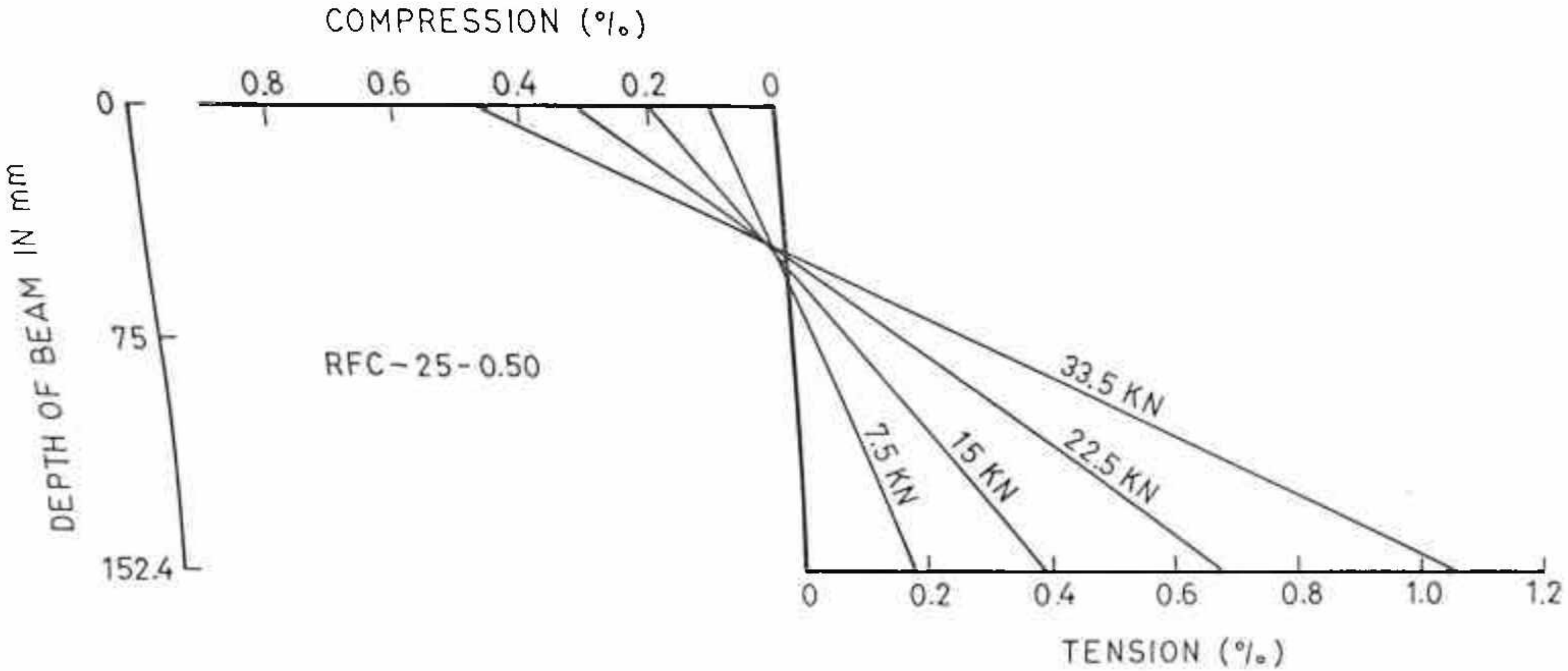


FIG.9.5 STRAIN DISTRIBUTION OF UNDER-REINFORCED FIBRE CONCRETE BEAMS AT CENTRAL SECTION

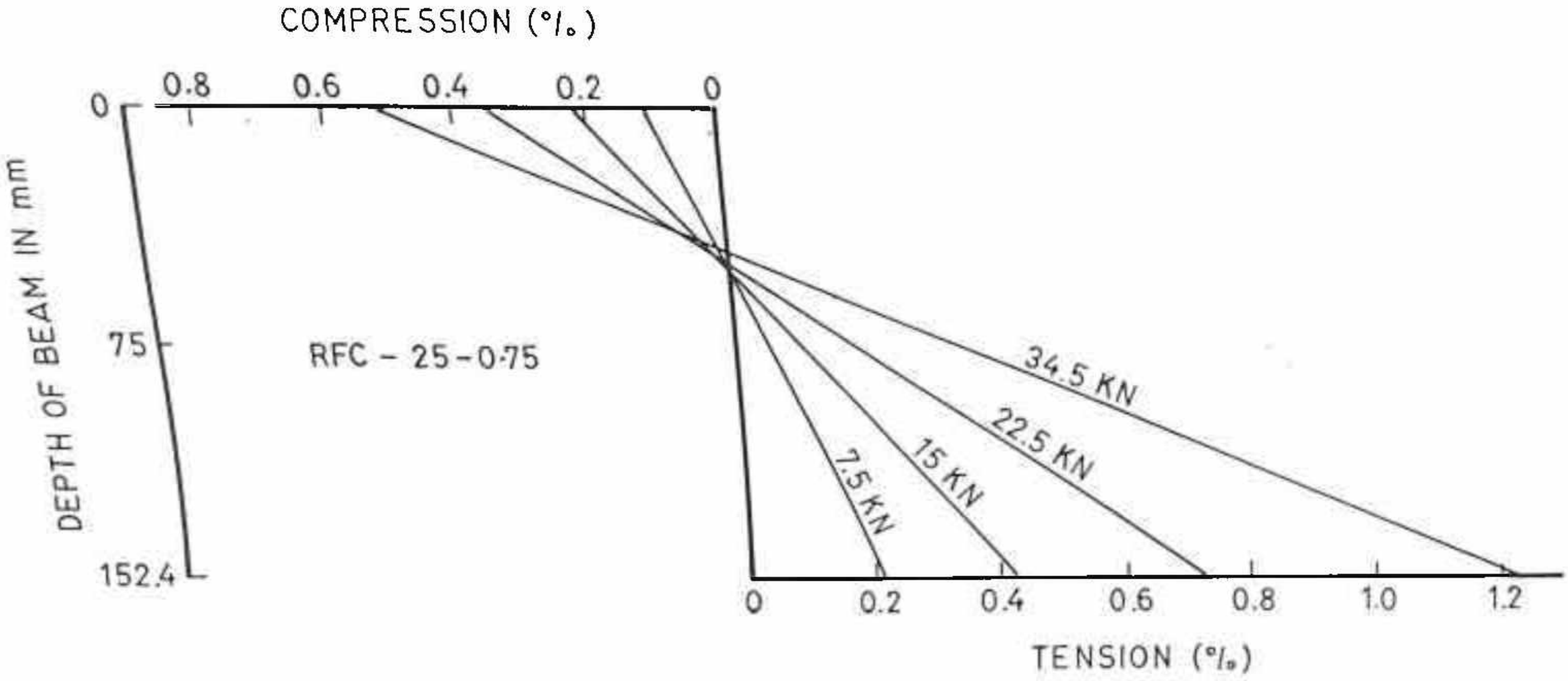


FIG.9.6 STRAIN DISTRIBUTION OF UNDER-REINFORCED FIBRE CONCRETE BEAMS AT CENTRAL SECTION

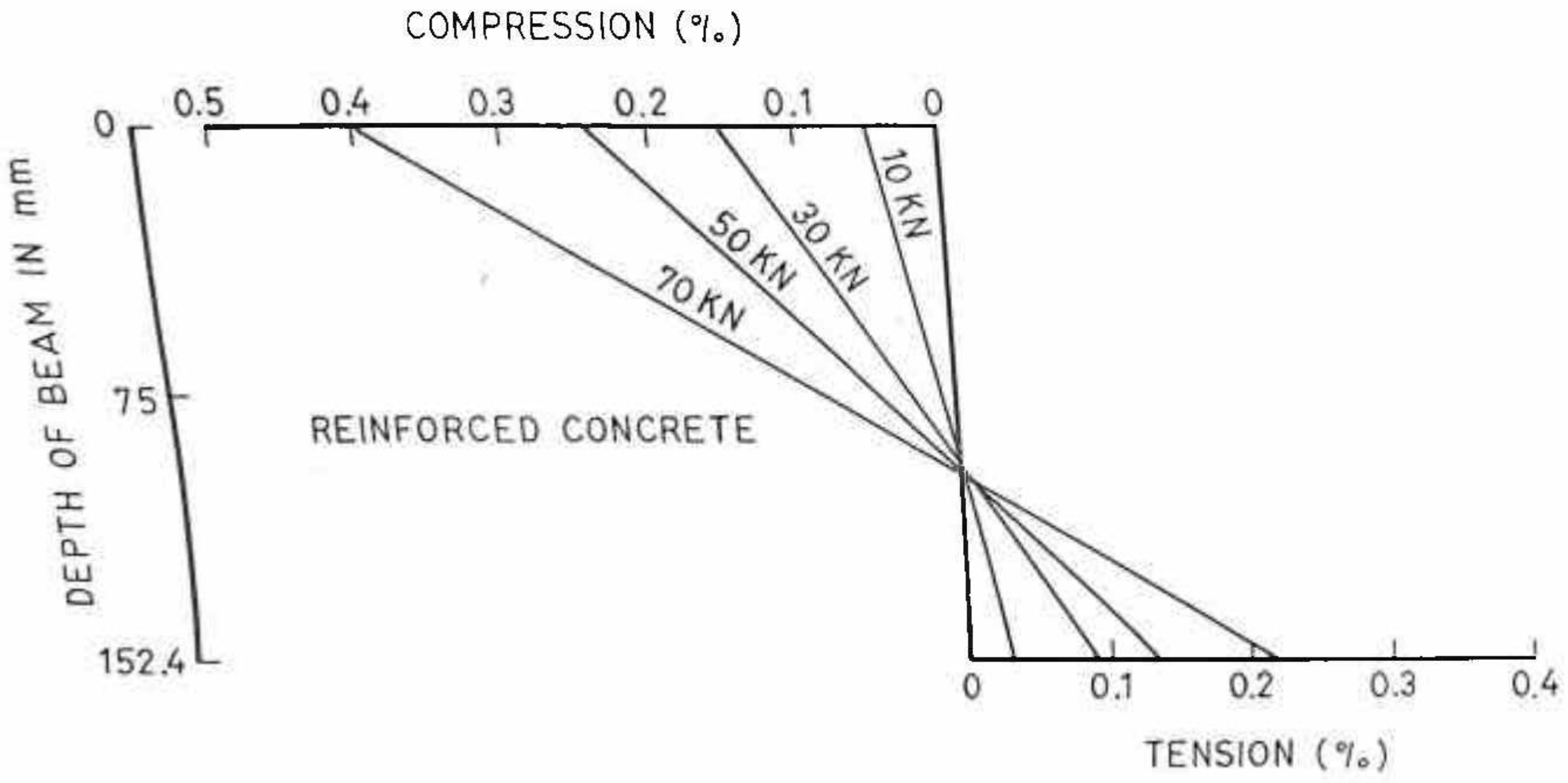


FIG.9.7 STRAIN DISTRIBUTION OF OVER-REINFORCED CONCRETE BEAMS AT CENTRAL SECTION

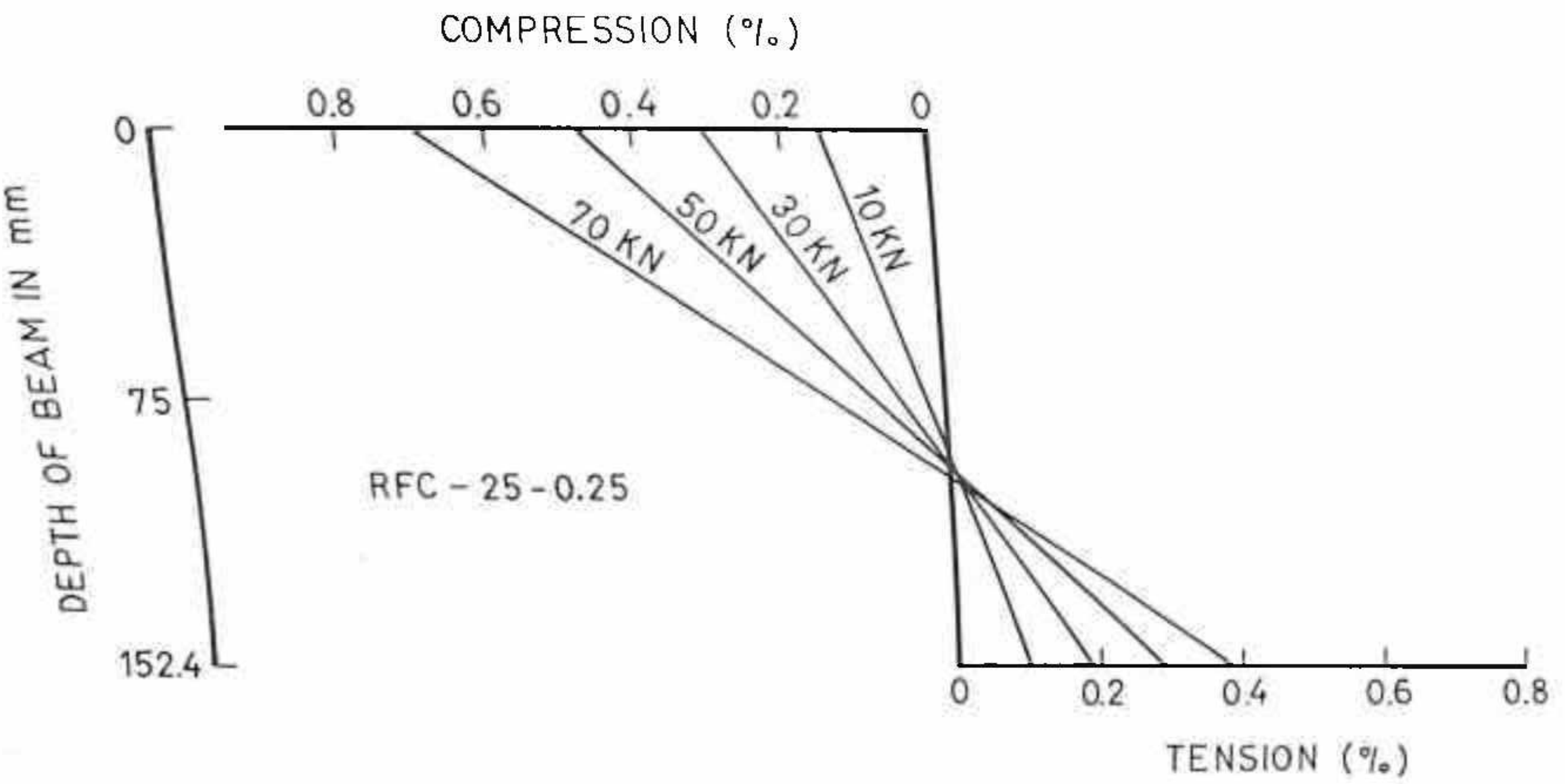


FIG. 9.8 STRAIN DISTRIBUTION OF OVER-REINFORCED FIBRE CONCRETE BEAMS AT CENTRAL SECTION

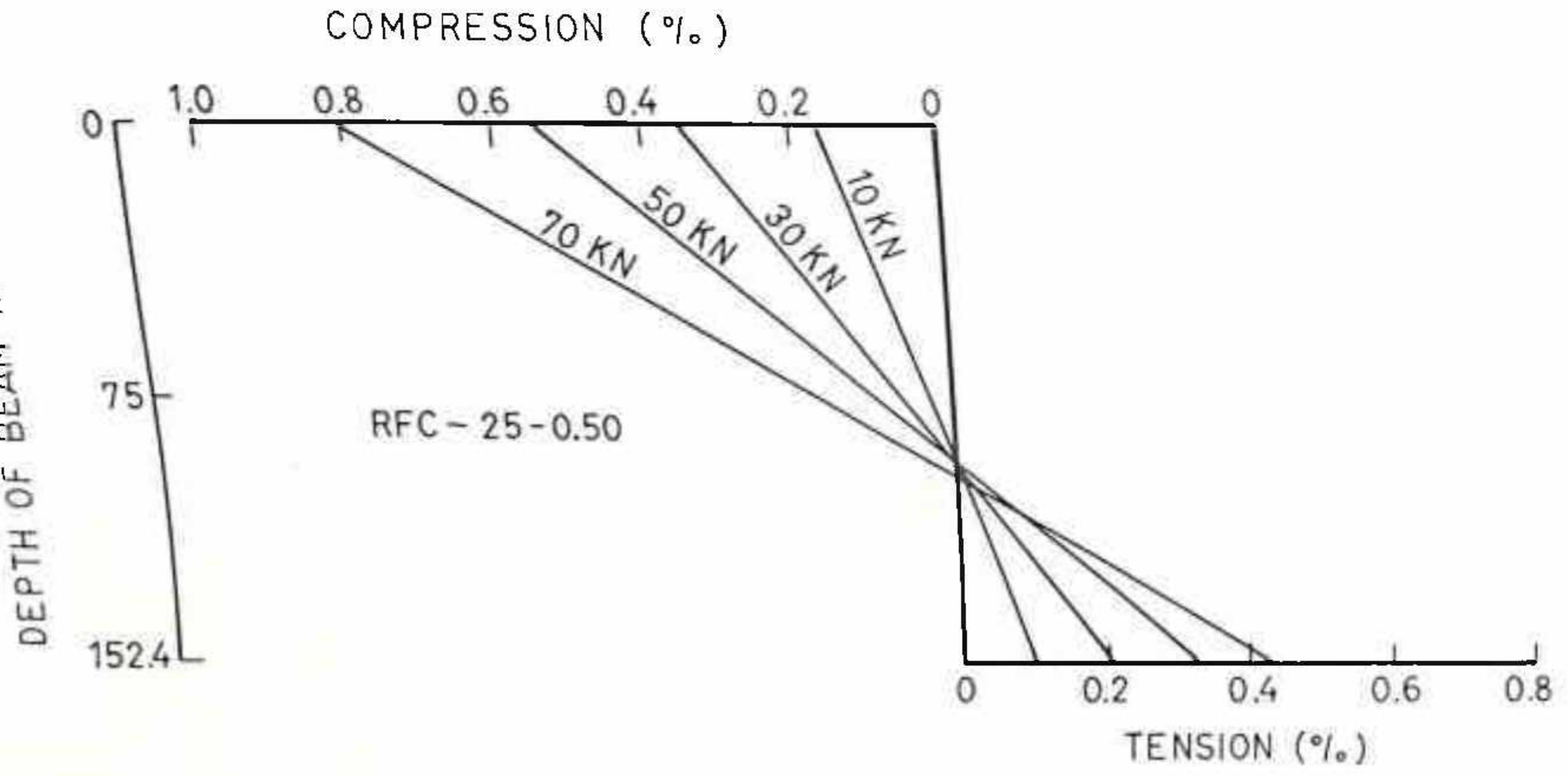


FIG.9.9 STRAIN DISTRIBUTION OF OVER-REINFORCED FIBRE CONCRETE BEAMS AT CENTRAL SECTION

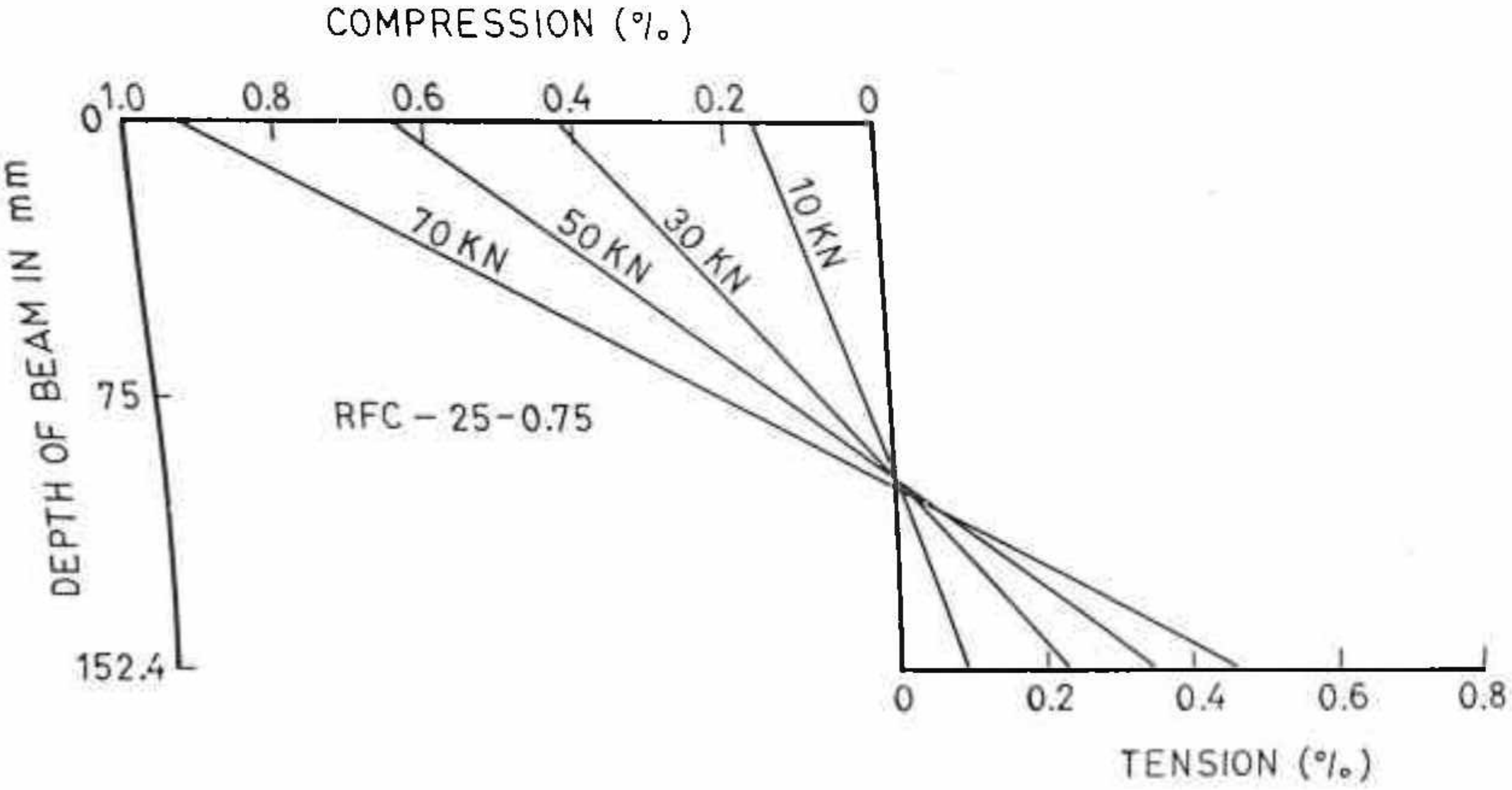


FIG.9.10 STRAIN DISTRIBUTION OF OVER-REINFORCED FIBRE CONCRETE BEAMS AT CENTRAL SECTION

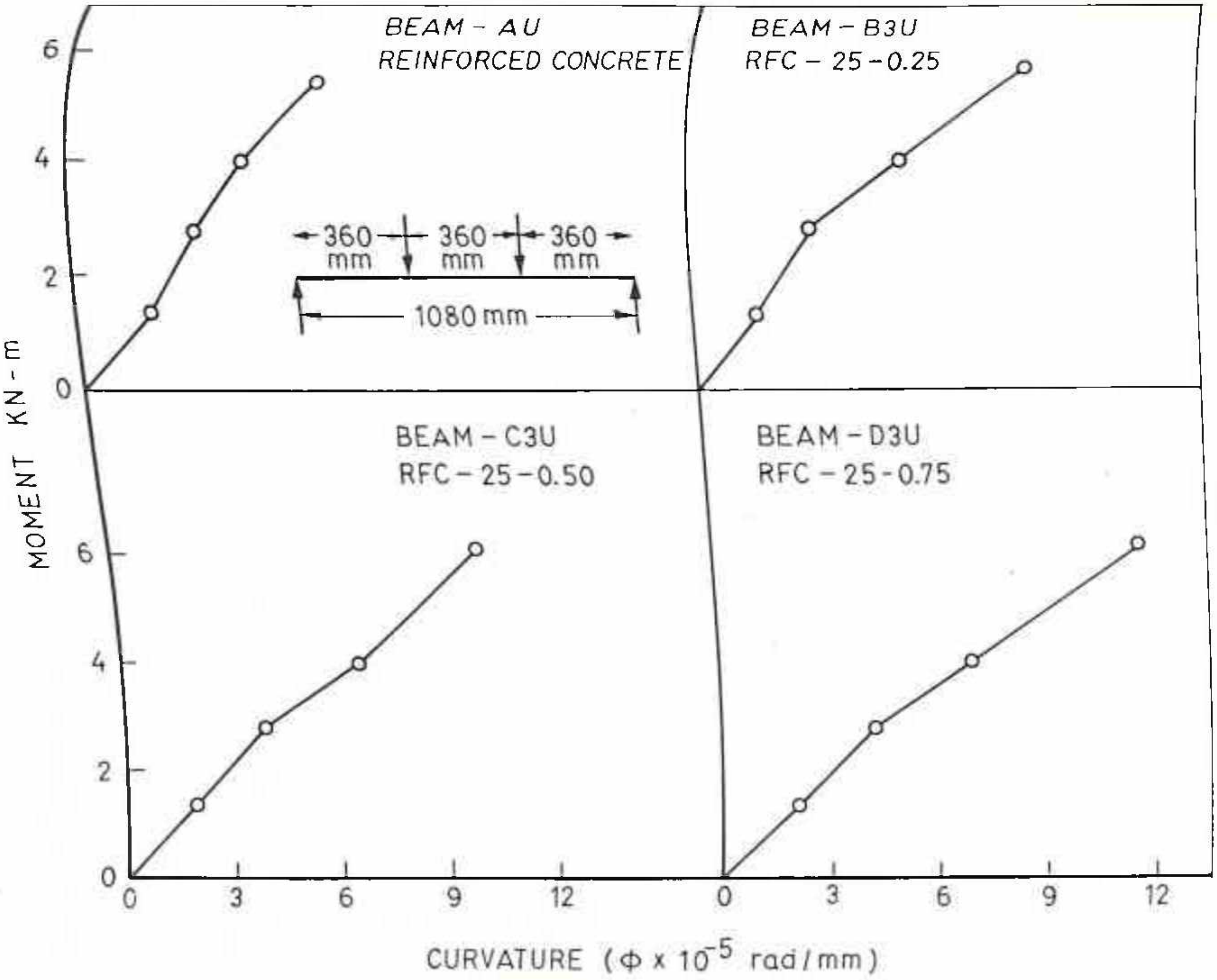


FIG. 9.11 MOMENT CURVATURE PLOTS AT CENTRAL SECTION OF UNDER-REINFORCED CONCRETE BEAMS

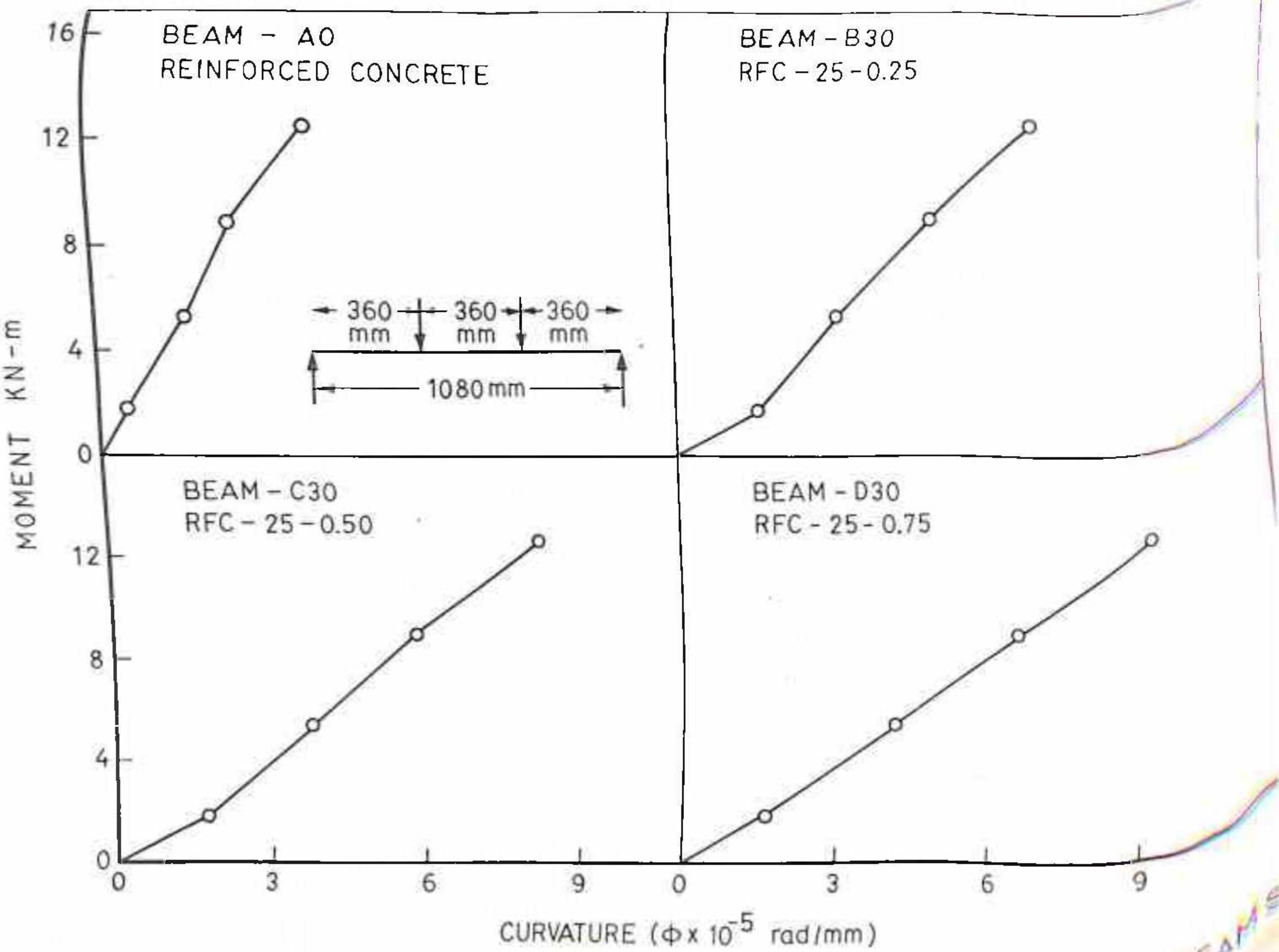


FIG.9.12 MOMENT-CURVATURE PLOTS AT CENTRAL SECTION OF OVER-REINFORCED CONCRETE BEAMS

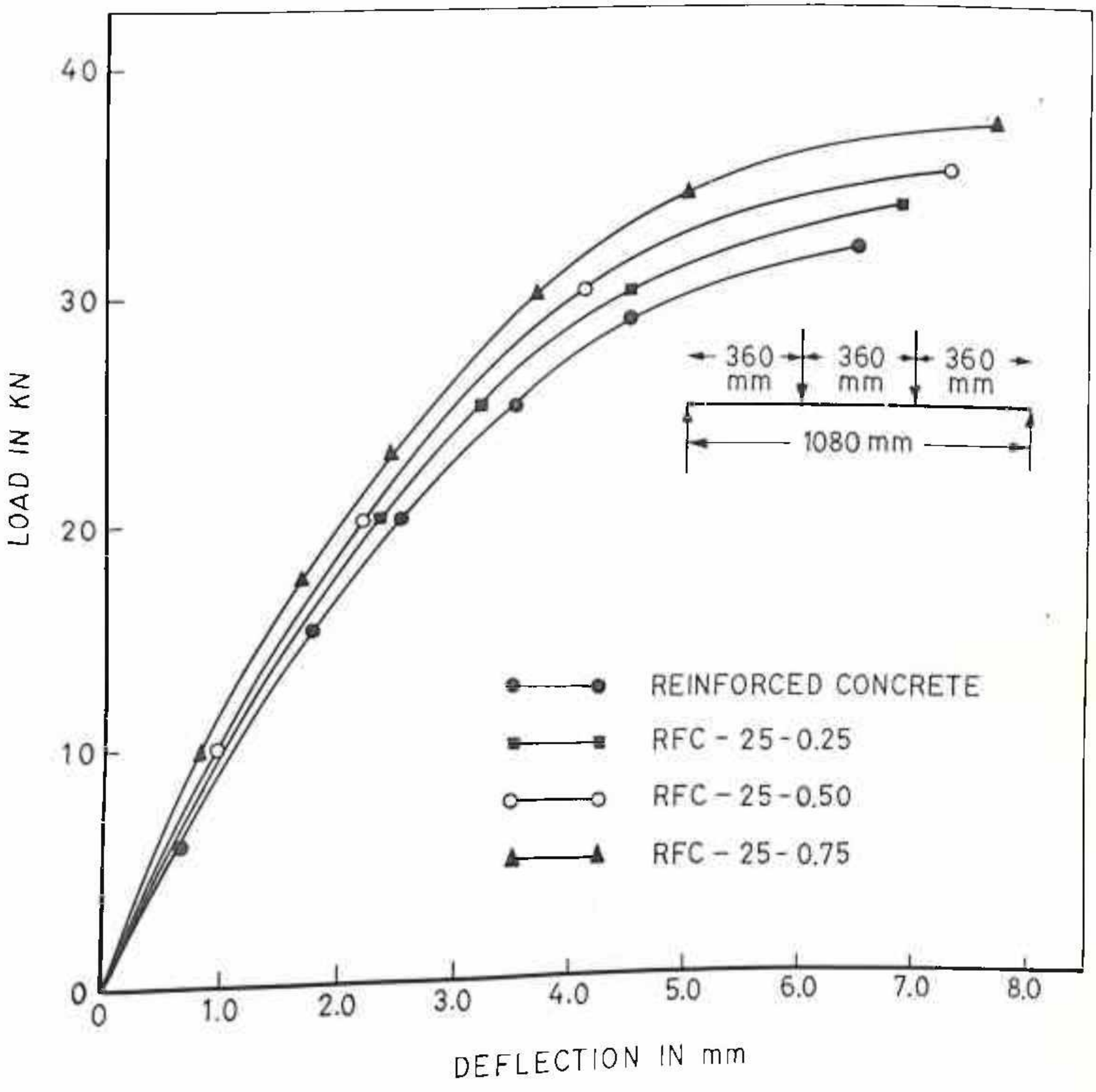


FIG. 9.13 LOAD-DEFLECTION CURVES OF UNDER-REINFORCED CONCRETE BEAMS AT CENTRAL SECTION

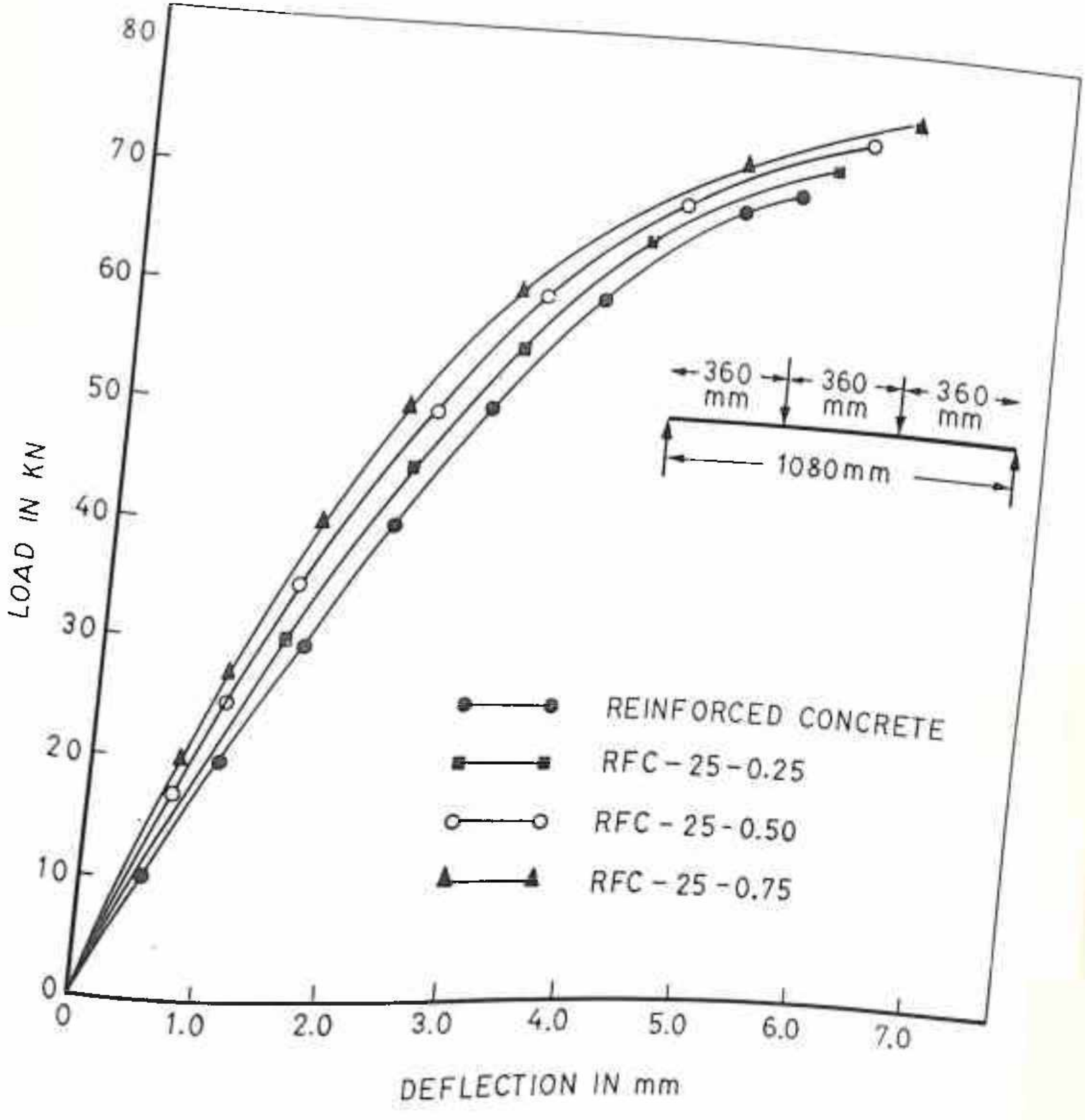


FIG. 9.14 LOAD-DEFLECTION CURVES OF OVER-REINFORCED CONCRETE BEAMS AT CENTRAL SECTION

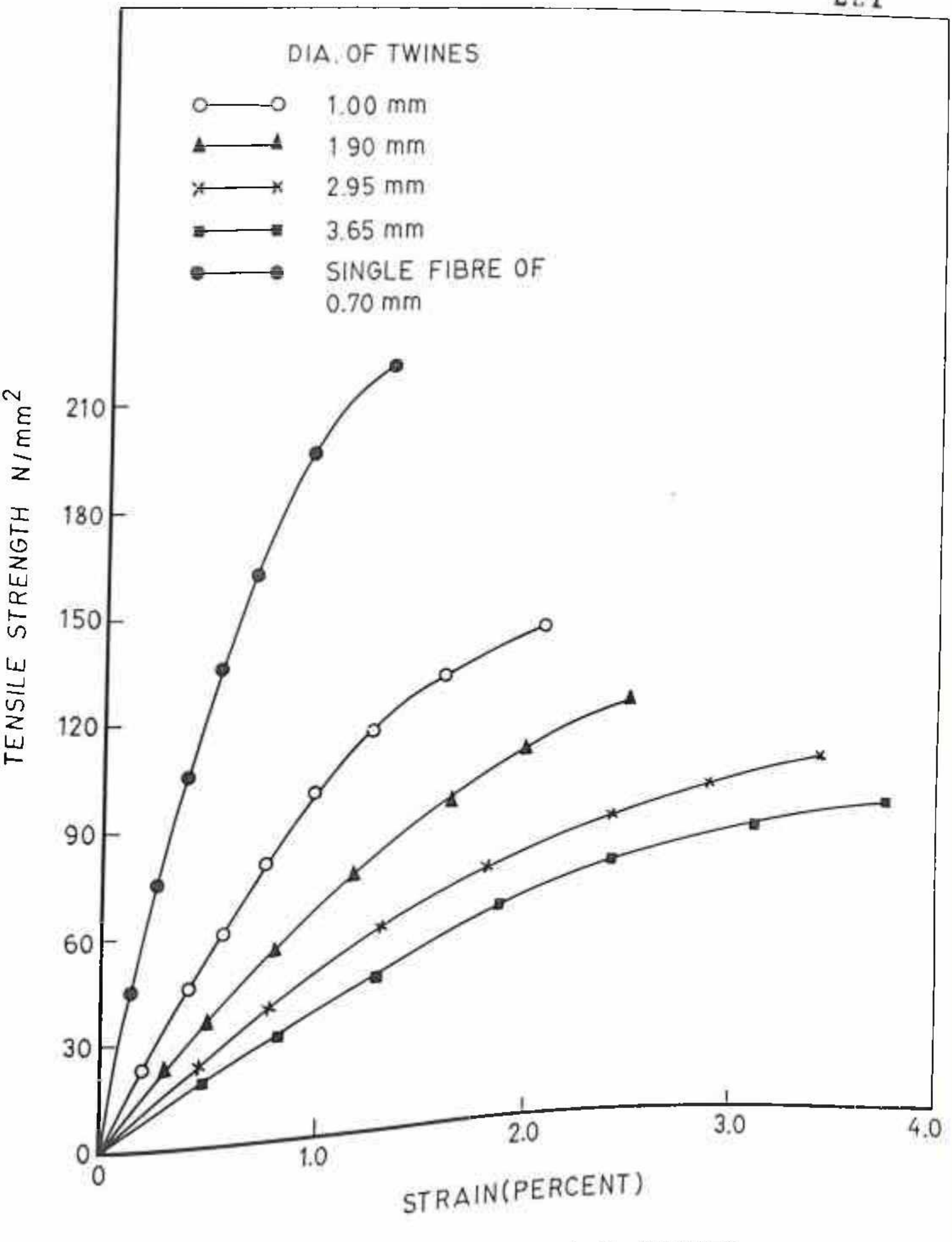


FIG. 9.15 STRESS-STRAIN CURVES OF TWINES

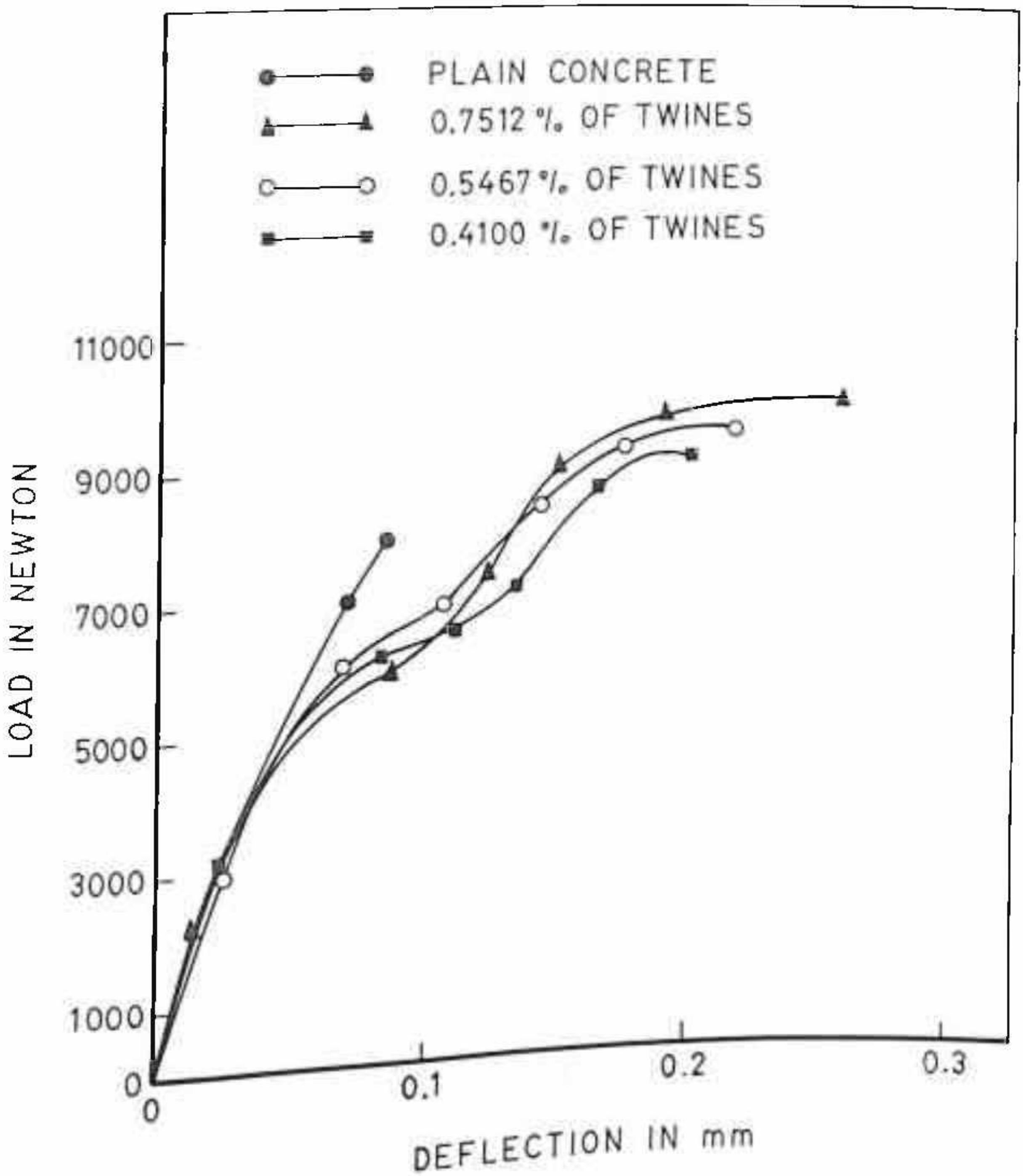


FIG. 9.16 LOAD-DEFLECTION CURVES OF CONCRETE BEAM REINFORCED WITH TWINES

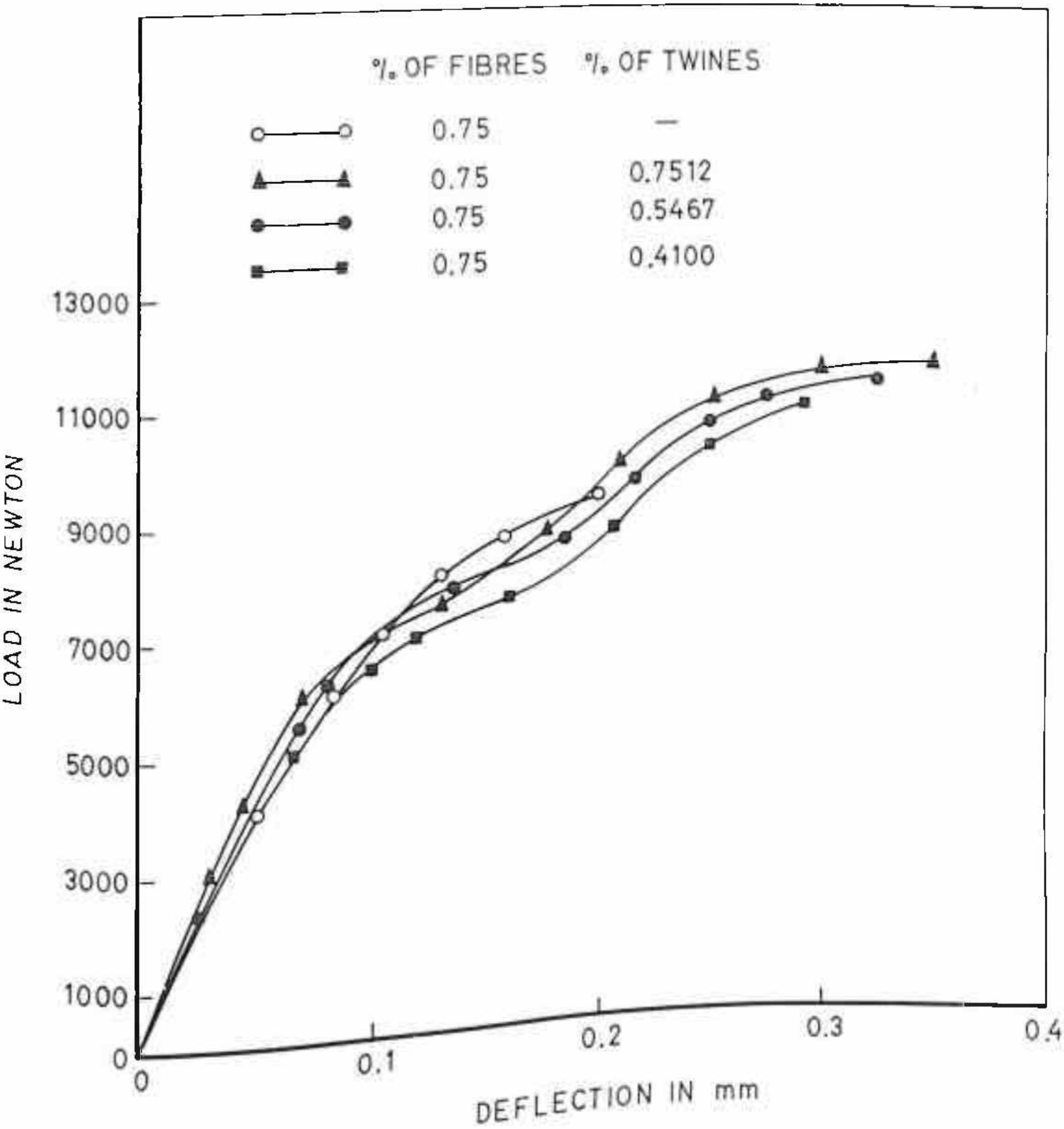


FIG. 9.17 LOAD-DEFLECTION CURVES OF CONCRETE BEAMS REINFORCED WITH TWINES AND FIBRES

CONCLUSIONS

The following conclusions can be drawn from the present study

1. San fibre has fairly good tensile strength of the order of 222.0 N/mm^2 in natural dry state, and its percentage elongation and initial tangent modulus are 1.25% to 1.34% and 2.2 x 10^4 N/mm^2 respectively.

2. San fibre absorbs water almost equal to its own weight at saturation. It is dimensionally stable and is durable in cement environment.

3. San fibres show adequate strength even under adverse alkaline medium like cement mortar and solution of NaOH of pH Value 11. The tensile strength of embedded fibres shows no loss of strength at the end of 3-4 months, thus indicating clearly that there will be no loss of fibre strength once the fibres are embedded in concrete. There is also no significant decrease in the percent elongation of the fibres when treated in a alkaline medium.

4. Addition of san fibres reduces the workability of the plain concrete. Addition of 1.5% of fibre reduces the compaction factor by 12 to 15%. Slump of plain concrete also gets reduced after the addition of fibres. Slump is practically zero for all the five fibre lengths beyond 1.00% of the fibre content.

5. Presence of san fibre in concrete does not affect its

compressive strength significantly for all fibre lengths and upto fibre content of 0.75%, but, beyond this percentage of fibre content, the strength decreases sharply because of "balling" and "lumping" of the fibres in concrete.

6. Split and flexural tensile strength of concrete is also increased with the addition of san fibres. Both the tensile strengths increase upto 0.75% of the fibre content, but, beyond this both the strengths start decreasing. The maximum increase in split tensile strength is 19.03% which occurs with 0.75% fibre of 25 mm length in concrete, and the maximum decrease in the strength is 17.33% with 1.5% of fibre content and fibre length 35 mm. Similarly the maximum increase (12.78%) in flexural tensile strength is with 0.75% of fibre content and 25 mm fibre length.

7. The experimental results of compressive strength, modulus of elasticity, split tensile strength and flexural tensile strength are in good agreement with the values obtained from the theoretical model which is based on the law of mixture. This is, however, so only upto 0.75% of the fibre content. The experimental results and the values obtained from theoretical model do not agree beyond 0.75% of the fibre content. Though as per the theoretical model, the strength should increase as the fibre percentage increases, in reality the strength start decreasing because of "balling" and "lumping" problems that arise

while mixing and compaction.

8. Stress-strain curves of san fibre reinforced concrete show that the ultimate strains at failure are much higher than that of plain concrete. It is concluded that the ductility of the concrete increases with the increase in fibre content.

9. The fracture toughness of concrete increases with the increase in fibre content. The maximum increase of 208% in fracture toughness of concrete is obtained with the fibre percentage of 0.75 and fibre length 30 mm.

10. The presence of san fibre improves the impact strength of concrete as found from the tests performed on cement concrete sheets. The maximum increase of 26.34% in the strength is observed with 0.75% of the fibre content and 25 mm fibre length. However, since in this work, impact strength tests were carried out only with three percentages of fibres viz. 0.25, 0.50, 0.75 and only one fibre length (optimum) viz. 25 mm, some more experiments can be carried out with greater volume percentages and lengths of fibres. Similarly some tests can also be performed with cement concrete sheets reinforced with fibre mesh.

11. The strength of san fibre reinforced concrete sheets is also found to have improved as compared to plain concrete sheets, when tested under static loading. Test results indicate that the strength improves by 15 to 20%. Addition of san fibres also

enhances the ductility of plain concrete sheets.

12. The addition of san fibres in conventionally reinforced (Under-reinforced and over-reinforced) concrete beams has the following effects on their performance

(a) The compressive strain in under-reinforced concrete beams is increased by 39.06% to 66.56%, where as in case of over-reinforced concrete beams it increases by 75% t 134.32% depending upon the volume percentage of the fibres. The maximum increase in compressive strains in both types of beams is observed with 0.75% of fibre by volume.

(b) There is marginal increase in the load carrying capacity of under-reinforced concrete beams at first crack (3.6% to 9.6%) and at failure (4.37% to 11.56%). Similarly in case of over-reinforced concrete beams, the increase is 1.53% to 3.84% at first crack, and 2.28% to 5.14% at failure. Under-reinforced concrete beams have higher increase in first crack load and ultimate load carrying capacity than over-reinforced concrete beams.

(c) The curvature increases with the increase in volume percentage of fibres in both under-reinforced and over-reinforced concrete beams. The maximum increase in curvature is 77.68% in case of under-reinforced concrete beams, and 129% in case of over-reinforced concrete beams. These increases in curvatures could be due to the fact that in order to mobilize the same amount of compressive force , the maximum strain of the fibre concrete would be higher because of greater ductility of the material.

(d) The average crack spacing and crack widths get reduced in both under-reinforced and over-reinforced concrete beams, when further reinforced with fibres because fibres act as crack arrester.

Since the results in respect of conventionally reinforced concrete beams further reinforced with fibres are based on the experiments conducted with only three percentages of fibres viz. 0.25, 0.50, 0.75 and only one fibre length i.e. 25 mm., there still remains a definite scope for some more investigations with various fibre lengths and percentages.

13. The results in respect of concrete beams reinforced with twines (made of san fibres) show encouraging trend. But there is still lot of scope for research to be carried out with different diameter of twines, percentages of twines, and by adopting different arrangement of placing and anchoring twines

REFERENCES

1. Romualdi, J.P. and Batson, G.B. Mechanics of crack arrest in concrete. Journal of Engg. Mechanics Division Proceedings. ASCE, Vol.89, EM 3, June 1963, pp.147-160.

2. Romualdi, J.P. and Batson, G.B. Behaviour of reinforced cement concrete beams with closely spaced reinforcement. Journal of the American Concrete Institute, Proceedings Vol.60, No.6, June 1963, pp.775-789.

3. Romualdi, J.P. and Mandel, J.A. Tensile strength of concrete affected by uniformly distributed and closely spaced short lengths of wire reinforcement. Journal of the American Concrete Institute, Proceedings. Vol.61, No.6, June 1964, pp.657-670.

4. Grimer, F.J. and Ali, M.A. The strength of cements reinforced with glass fibres. Magazine of concrete research, Vol.21, No.66, March 1969, pp.23-30.

5. Shah, S.P. and Rangan, B.V. Effects of reinforcements on ductility of concrete. Journal of the Structural Division Proc., ASCE, Vol.96, ST 6, June 1970, pp.1167-1184.

6. Rajagopalan, K., Parameswaran, V.S. and Ramaswamy, G.S. Strength of steel fibre reinforced concrete beam. The Indian concrete journal, Vol.48, No.1, Jan 1974, pp.17-25.

7. Swamy ,R.N. Fibre reinforced concrete :Mechanics, Properties and Applications. Indian Concrete Journal, Vol.48, No.1, Jan 1974, pp.7-16.

8. Anon Fibrous concrete overlay gets the big test. Concrete Construction, Vol.19, No.3, March, pp.103-105, 1974

9. Harris, B. The fracture behaviour of fibre reinforced concrete. Cement and Concrete Research, Vol.2, No.4, July 1972, pp.447-461.

10. Swamy, R.N. and Mangat, P.S. A theory for the flexural strength of steel fibre reinforced concrete. Cement and Concrete Research, Vol.4, No.2, March 1974, pp.313-335.

11. Pakotiprapha, B., Pama, R.P. and Lee, S.L. Mechanical properties of cement mortar with randomly oriented short steel wires. Magazine of Concrete Research, Vol.26, No.86, March 1974, pp.3-15.

12. Tattersall, G.H. and Urbanowicz, C.R. Bond strength in steel fibre reinforced concrete. Magazine of concrete research, Vol.26, No.87, June 1974, pp.105-113.

13. Hannant, D.J. and Spring, N. Steel fibre reinforced mortar : A technique for producing composites with uniaxial fibre alignment. Magazine of Concrete Research, Vol.26, No.86, March 1974, pp.47-48.

14. Kar, J.N. and Pal, A.K. Strength of fibre reinforced concrete. Journal of the Structural Division, Proc. ASCE, Vol. 98, (ST-5), May 1972, pp.1053-1068.

15. Ramey, M.R. Compression fatigue of fibre reinforced concrete. Journal of Engineering Mechanics Division, ASCE, Vol.100, EM 2, April 1974, pp.139-149.

16. Shah , S.P. and Vijayarangan, B. Fibre reinforced concrete properties. Journal of American Concrete Institute Proceedings Vol.68, No.2, Feb 1971, pp.126-135.

17. Chen, Kiai- Fah and Carson, J.L. Stress-strain properties of random wire reinforced concrete. Journal of American Concrete Institute, Proceedings Vol.68, No.12, Dec 1971, pp.933-936.

18. Snyder, M.J. and Lankard, D.R. Factors affecting the flexural strength of steel fibrous concrete. Journal of American Concrete Institute, Proceedings Vol.69, No.2, Feb 1972, pp.96-100.

19. Anon. Properties of fibre reinforced concrete. Precast Concrete, Vol.2, No.12, Dec 1971, pp.709-711.

20. Anon. Ordinary portland cement concrete reinforced with glass fibres. Precast Concrete, Vol.3, No.11, Nov 1972, pp.681-684.

21. Fibre reinforced concrete. Proceedings of the International

Symposium Ottawa, Oct 1973, Publication of ACI, SP-44, 1974, pp.554.

22. Shah, S.P. New reinforcing materials in concrete. Journal of the American Concrete Institute, Vol.71, No.5, May 1974, pp.257-262.

23. Johnston, C.D. and Coleman, R.A. Steel fibre reinforced mortar and concrete A review of the mechanical properties. American Concrete Institute Publication, Fibre reinforced concrete, July 1974, pp.127-142.

24. State of the art report on fibre reinforced concrete - Reported by ACI Committe 544, Journal of American Concrete Institute, Proceedings Vol.70, Nov 1973, pp.729-744.

25. Gunasekaran, M. The strength and behaviour of light weight concrete reinforced with metallic fibres of mixed aspect ratios. Indian concrete Journal, Vol.49, No.2, Feb 1975, pp.48-49. & 55 .

26. Krishna Raju, N. et al. Compression strength and bearing strength of steel fibre reinforced concrete. Indian Concrete Journal, Vol.51, No.6, June 1977, pp.103-108.

27. Hale, D. K. Fibre pull out in multiply cracked discontinous fibre composites. Rilem Symposium on Fibre Reinforced Cement and Concrete, Sep 1975, pp.55-68.

28. Swamy, R.N. and Mangat, P.S. The interfacial bond stress in steel fibre cement composites. Cement and Concrete Research, Vol.6, No.5, 1976, pp.641-650 .

29. Swamy, R.N. and Mangat, P.S. The on set of cracking and ductility of steel fibre reinforced concrete. Cement and Concrete Research, Vol.5, No.1, Jan 1975, pp.37-53.

30. Krenchel, H. Fibre spacing and specific fibre surface. Rilem Symposium and Fibre Reinforced Cement and Concrete, Sep. 1975, pp.69-80.

31. Swamy, R.N. and Mangat, P.S. Flexural strength of steel fibre reinforced concrete. Institution of Civil Engineers Proceedings Part 2, Research and Theory, Vol.57, Dec. 1974, pp. 701-707.

32. Hughes, B.P. and Fattuhi, N.I. The workability of steel fibre reinforced concrete. Magazine of Concrete Research, Vol. 28, No.96, Sept 1976, pp.157-161.

33. Hughes, B.P. and Fattuhi, N.I. Stress-strain curves for fibre reinforced concrete in compression. Cement and concrete Research, Vol.7, 1977, pp.173-184.

34. Frondistou Yannas, S. Flexural strength of concrete with randomly oriented glass fibres. Magazine of Concrete research, Vol.29, No.100, September 1977, pp.142-146.

35. Kasperkiewicz, J. Fibre spacing in steel fibre reinforced composites. Materiaux Et Constructions, Vol.10, No.55, pp.25-31, 1977

36. Komlos, K. Uniaxial tensile strength of early age fibre concretes. Materiaux Et Constructions, Vol.12, No.69, pp.201-205, 1979

37. Swamy, R.N. and Stavrides, H. Influence of the method of fabrication on strength properties of steel fibre concrete. Materiaux Et Constructions, Vol.19, No.52, pp.243-252, 1978

38. Samarai, M.A. and Elvery, R.H. The influence of fibres upon crack development in reinforced concrete subjected to uniaxial tension. Magazine Of Concrete Research, Vol.26, No.89, Dec 1974, pp.203-211.

39. Hughes, B.P. and Fattuhi, N.I. Fibre bond strengths in cement and concrete. Magazine of Concrete Research, Vol.27, No.92, Sep 1975, pp.161-166.

40. Schnutgen, B. Some results of the investigation on steel fibre reinforced concrete. Symposium on Fibre Reinforced Cement and Concrete , Sep. 1975, pp.105-118.

No.92, Sept 1975, pp.167-170.

41. Naaman, A.E. and Shah, S.P. Pullout mechanism in steel fibre reinforced concrete. Proceedings ASCE , Vol.102, ST8, August 1976, pp.1537-1548.

42. Uzomaka, O.J. Characteristics of Akwara on a reinforcing fibre. Magazine of Concrete Research, Vol.28, No.96, Sep 1976, pp.162-167.

43. Lewis, G. and Premalal, M. Natural vegetable fibres as reinforcement in cement sheets. Magazine of Concrete research, Vol.31, No.107, June 1979, pp.104-108.

44. Dinesh, Mohan and Rehsi, S.S. Steel fibre reinforced concrete roofing units. Indian Concrete Journal, Vol.51, No.12, June 1977, pp.370-373.

45. Mangat, P.S. Tensile strength of steel fibre reinforced concrete. Cement and Concrete Research, March 1976, Vol.4, pp. 245-252.

46. Kukreja, C.B., Kaushik, S.K., Kanchi, M.B. and Jain, O.P. Flexural characteristics of steel fibre reinforced concrete. Indian Concrete Journal, July 1980, pp.184-188.

47. Walkus, B.R., Januszkiewicz, A. and Jeuzal, J. Concrete composites with cut steel fibre reinforcement subjected to uniaxial tension. Journal of the American Concrete Institute, Vol.76, Oct 1979, pp.1079-1092.

48. Castro, J. and Naaman, A.E. Cement mortar reinforced with natural fibres. Americanm Concrete Institute Journal, Jan-Feb 1981, pp.69-78.

49. Measurement of properties of fibre reinforced concrete. Reported by ACI Committe 544. American Concrete Institute Journal, July 1978, pp.283-289.

50. Ramakrishnan, V., Bradshang, T., Coyle, H.V. and Sehrader. A comparative evaluation of concrete reinforced with steel fibres of deformed ends glued together into bundles. Journal of the American Concrete Institute, Proceedings Vol.77, No.3, May-June 1980, pp.135-143.

51. Swamy, R.N. and Al-Taan, S.A. Deformation and ultimate strength in flexure of reinforced concrete beams made with steel fibre concrete. Journal of the American Concrete Institute, Vol. 78, No.5, Sep- Oct 1981, pp.395-405.

52. Barr, B. and Mohamad Noor, M.R. The toughness index of steel fibre reinforced concrete. American Concrete Institute Journal, Sep-Oct 1985, pp.622-629.

53. Fanella, D.A. and Naaman, A.E. Strain properties of fibre reinforced mortar in compression. American Concrete Institute Journal, Jul-Aug 1985, pp.475-482.

54. Ramakrishnan, V. and Senthil Kumar, M. Constitutive relations and modeling for concrete fibre composites - A state of the art report. Proceedings of the International Symposium on fibre reinforced concrete, Dec 16-19, 1987, Madras, India, pp.

1.21 1.55.

55. Shah, S.P. Strength evaluation and failure mechanics of fibre reinforced concrete. Proceedings of the International Symposium on fibre reinforced concrete. Dec 16-19, 1987, Madras, India, pp.1.3-1.19.

56. Khan, T. Abdul Hafeez, Laid, Samal Mohamed and Ramakrishna, B. Experimental study of SFRC under compression, Indirect tension and pure bending .Proceedings of the International Symposium on fibre reinforced concrete. Dec 16-19, 1987, Madras, India, pp.2.39-2.47.

57. Paramasivam, P., Lim, T.Y. and Lee, S.L. Flexural behaviour of reinforced steel fibre concrete beams. Proceedings of the International Symposiumon fibre reinforced concrete, Dec 16-19, 1987, Madras, India, pp.1.79-1.89.

58. Nagarkar, P.K. , Tambe, S.K. and Pazare, D.G. Study of fibre reinforced concrete. Proceedings of the International Symposium on fibre reinforced concrete, Dec 16-19, 1987, Madras, India, pp.2.131-2.141.

59. Corradini, G., Seoccia, G. and Volpe, R. Statistical evaluation of the effects of cement content, water cement ratio and fibre content on the physical-mechanical properties of a steel fibre reinforced concrete. Proceedings of the International Symposium on fibre reinforced concrete, Dec 16-19, 1987, Madras,

India , pp.1.185-1.195.

60. Achyutha, H. and Sabapathi, P. Cracking characteristics of R.C. beams with steel fibres. Proceedings of the International Symposium on fibre reinforced concrete, Dec 16-19, 1987, Madras, India, pp.2.59-2.68.

61. Ramakrishna, V. and Josifek, C. Performance characteristics and flexural fatigue strength of concrete steel fibre composites, Proceedings of the International Symposium on fibre reinforced concrete, Dec 16-19, 1987, Madras, India, pp.2.73.

62. Kukreja, C.B., Kanchi, M.B., Kaushik, S.K. and Jain, O.P. Ultimate strength of fibre reinforced concrete slabs. Proceedings of the International Symposium on fibre reinforced concrete, Dec 16-19, 1987, Madras, India, pp.2.237-2.555.

63. Srinivas, Y.M. , Gupte, K.A. and Rau, R.H.G. Ultrahigh strength steel fibres for concrete reinforcement. Proceedings of the International Symposium on fibre reinforced concrete, Dec 16-19, 1987, Madras, India, pp.2.121-2.129.

64. Dwarakanath, H.V. and Nagaraj, T.S. Flexural behaviour of reinforced fibre concrete beams. Proceedings of the International Symposium on fibre reinforced concrete, Dec 16-19, 1987, Madras, India, pp.2.49-2.58 .

65. Halvorsen, G.T. and Kesler, C.E. Moment curvature relationships for concrete beams with plain and deformed fibres. Journal of the American Concrete Institute, Proceedings Vol.76, No.6, June 1975, pp.697-706.

66. Guide for specifying , mixing , placing and finishing steel fibre reinforced concrete. Journal of the American Concrete Institute, Mar-Apr 1984, pp.140-147.

67. Nagaraja, R. and Swami, B.L.P. Fibre reinforced concrete with non-metallic fibres - An experimental study. Proceedings of the International Symposium on fibre reinforced concrete, Dec 16-19, 1987, Madras, India.

68. Islam, Md. Rafqul and Alam, A.K.M.khorshed. Study of fibre reinforced concrete with natural fibres . Proceedings of the International Symposium on fibre reinforced concrete,Dec 16-19, 1987, Madras, India.

69. Kukreja, C.B. and Chawla, Sanjeev. Flexural characteristics of steel fibre reinforced concrete. Indian Concrete Journal, March 1989, pp.184-188.

70. Pomeroy, C.D. An assessment of the commercial prospects for fibre and polymer modified concretes. Magazine of Concrete Research, Vol.28, No.96, Sep 1976.

71. Sabapathi, P. and Achyutha, H. Analysis of steel fibre reinforced concrete beams. Indian Concrete Journal, May 1989, pp.246-252.

72. Colin, D. Johnston and Robert, H. Zemp. Flexural fatigue performance of steel fibre reinforced concrete- Influence of fibre content,aspect ratio and type. American Concrete Institute materials Journal, Jul-Aug 1991, pp.374-383.

73. Gopalaratnam, V.S., Shah, S.P., Batson, G.B., Criswell, M.E., Ramakrishnan, V. and Wecharatana Methi. Fracture toughness of fibre reinforced concrete. American Concrete Institute materials Journal, Jul-Aug 1991, pp.339-355.

74. Ezeldin, A.sameer and Steven, R.Lowe. Mechanical properties of steel fibre reinforced rapid set materials. American Concrete Institute materials Journal, Jul-Aug 1991, pp. 384-389.

75. Kosa, K., Naaman, A.E. and Hansen, W. Durability of fibre reinforced mortar. American Concrete Institute materials Journal, May-June 1991, pp.310-319.

76. Mangat, P.S. and Motamedi, A.A. Compression creep behaviour of steel fibre reinforced cement composites. Materiaux Et Constructions, Vol.19 , No.113, pp.361-369, 1986

77. Grzybowski, M. and Shah, S.P. Model to predict cracking in the fibre reinforced concrete due to restrained shrinkage.

Magazine of Concrete Research, Vol.41, No.148, Sep. 1989, pp. 125-136.

78. Mawenya, A.S. Developements in sisal fibre reinforced concrete. Proceedings Symposium on approriate building materials for low cost housing, Nairobi, Kenya, Nov 7-14, 1983.

79. Fageiri, O.M.E. Use of kenaf fibres for reinforcement of rich cement -sand corrugated sheets. Proceedings Symposium on approriate building materials for low cost housing. Nairobi, Kenya, Nov 7-14, 1983.

80. Saluja, S.K., Sarma, M.S., Singh, A.P. and Sunil Kumar. Compressive strength of fibrous concrete. The Indian Concrete Journal, February 1992, pp.99-102.

81. Siddique, R. and Venkataramana, J. Cement concrete reinforced with natural fibres - San fibre a possibility. Proceedings national seminar on low cost building material and technologies. 20-21st March, Anantapur, India, 1992

82. Panarese, W.C. Fiber : Good for the concrete diet ?. Civil Engineerig, May 1992, pp 44-47.

83. Siddique, R. and Venkataramana, J. Use of san fibre in cement concrete sheets. American Concrete Institute fall convention of thin reinforced products. Puerto Rico, 24-30th Oct'1992.

84. Mwamila, B.L.M. Reinforcement of concrete beams with low modulus materials in form of twines. Proceedings Symposium on appropriate building materials for low cost housing, Nairobi, Kenya, Nov. 7-14, 1983.

85. Robert, C., Jack, D., Lawrence, D., Robert, L., and John, F. Inelastic behaviour of reinforced fibrous concrete. Journal of Structural Engineering. , Vol.113, No.4, April 1987, pp.802-817.

86. Dwarakanath, H. V. and Nagaraj, T. S. Deformational behaviour of reinforced fibre reinforced concrete beams in bending. Journal of Structural Engineering, ASCE, Vol.118, No.10, October, 1992 pp.2691-2698.

LIST OF PUBLICATIONS

1. Siddique, R. and Venkataramana, J., " Cement concrete reinforced with natural fibres - San fibre a possibility", Proceeding National Seminar on Low Cost Building Materials & Technologies, March 20-21, 1992, Anantapur, India.

2. Siddique, R. and Venkataramana, J., "Use of san fibre in cement concrete sheets", American Concrete Institute Fall Convention on Thin Reinforced Products, October 24-30, 1992, Puerto Rico.

3. Siddique, R., "Fibre reinforced concrete composites", Proceeding UGC Seminar On Modern Trends In Civil Engineering, February 27-28, 1993, B.I.T.S., Pilani.

4. Siddique, R., and Sahay, R. N., "Study of concrete beams reinforced with natural fibres", Proceeding International Symposium On Strides In Civil Engineering, March 10-12, 1993, Madras.

5. Siddique, R. and Sahay, R. N., " Toughness of san fibre reinforced concrete", International Conference On "Our World In Concrete & Structures", August 25-27, 1993, Singapore. (Accepted)

6. Siddique, R., "Impact strength of san fibre reinforced concrete", International Symposium on "Innovative World of Concrete", August 30-September 3, 1993, Bangalore. (Accepted)

7. Siddique, R., "Properties of concrete reinforced with low percentage of synthetic fibres", American Concrete Institute Fall Convention's technical session on use of low fibre content fibre reinforced concrete in fibre slab applications, November 7-12, 1993, Minneapolis, Minn, U.S.A. (Accepted)

8. Siddique, R. and Venkataramana, J., "Compressive strength of fibre reinforced concrete", Journal of Civil Engineering and Construction Review. (Communicated)

9. Siddique, R. and Sahay, R. N., "Properties of cement concrete reinforced with san fibre", Journal of Materials in Civil Engineering, American Society of Civil Engineers. (Communicated)

BIO-DATA

Name: RAFAT SIDDIQUE

Date of Birth: 08-07-1966

Place of Birth: Hamirpur (U.P.)

Qualifications:

1. B.Sc Engg.(Civil) from Regional Engineering College, Rourkela(Orissa) in 1986
2. M.E. from B.I.T.S., Pilani (Rajasthan) in Dec'1988

Experience:

1. Lecturer in Civil Engineering Group, B.I.T.S., Pilani (Rajasthan) since Jan'1989
2. Nucleus Member, Distance Learning Programmes Unit, B.I.T.S., Pilani (Rajasthan)

Membership:

1. Associate Member, Institute Of Engineers (India)
2. Life Member, Indian Society For Technical Education