Melt extract and D-form steel fibres in cement composites

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MELT EXTRACT AND D-FORM STEEL FIBRES IN CEMENT COMPOSITES

by

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SUMMARY

This work on Arjex melt extract steel fibres and D-form fibres comprises three sections.

The aim of the first section is to provide design information relating workability to the flexural strengths by introducing different percentages of steel fibres into different mixes.Conplast 337 was introduced to increase the strength.

In the second section the investigation was centred on thin steel fibre reinforced cement sheets as alternatives to glass reinforced cement sheets.Two different rich mixes in cement were tried with different percentages of fibres and different thickness. The tests were carried out at 14 and 28 days.

Finally the third section was reserved for the use of steel fibres for localised crack control.This consisted of using thin layers of mortar boards containing steel fibres to provide a skin on the tensile face of a beam.Different percentages were used in different thicknesses of layers.

It was found that the Arjex melt extract steel fibres and the D-form steel fibres were more workable than a wide range of commercially available drawn wire steel fibres.Even at a weight of fibres equal to 12 % of the weight of the matrix the V-B time was still low. In the course of the experiments it was found that the slump test was very suitable to be carried out on site.The benefit gained from adding conplast 337 was an increase in strength , achieved in a cheaper manner than by the addition of more fibres and without loss of workability .

Since these fibres are of stainless steel with rust resistant

qualities and cost about three-quarters of the price of conventionally drawn carbon steel fibres, it was decided to incorporate them in thin sheets. This was intended to replace the Cem-fil glassfibre which undergoes some changes in its mechanical properties as a result of both physical and chemical actions, despite its inherently high alkali resistance. The melt extract steel fibre cement composites were capable of reaching a modulus of rupture (M.O.R.) of over 26 N/mm^2.

In the last part of the research it was found that the melt extract and D-form steel fibres can have a measurable effect on controlling cracks, using mortar boards on the tensile face of the beam.

Acknowledgements

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CHAPTER ONE : INTRODUCTION

1.1 Introduction

The inclusion of various types of fibres, natural or synthetic, in matrices weak in tension, to improve its properties has been carried out for many hundreds of years. The first major application was the use of straw to reinforce unbaked bricks. Horse hair was used to reinforce plaster and asbestos fibres have been used to reinforce Portland cement.

However, fibre reinforced cement based material is a more recent development. It was introduced to overcome the inherently brittle type of failure and increase the toughness of the matrix.

The replacement of existing materials with man - made fibres which would overcome these problems and those relating to the supply of asbestos in the long run , little impact resistance, and health hazards , was inevitable.

Among the new fibres developed are the steel fibres. The aims of inclusion of fibres in concrete and cement are as follows:

i) To improve the tensile or flexural strength;

ii) To improve the impact strength;

iii) To control cracking and the mode of failure by means of post - cracking ductility;

iv) To change the rheology characteristics of the material in the fresh state.

In less than a decade , research and development has transformed steel fibre concrete and cement materials from a laboratory curiosity into practical reality. The properties of fibre reinforced cement depends primarily upon the physical properties of the fibres , the matrix and the strength of the bond between the two.

The effectiveness of reinforcement depends on the following factors[1]:

i) Modular ratio E fibre/E matrix;

ii) Volume content of fibres;

iii) Fibre orientation;

iv) Fibre aspect ratio (length/diameter);

v) Fibre geometry - shape, length and diameter.

Generally the strength of the composite increases with:

i) Increase in modular ratio;

ii) Increase in fibre content;

iii) Increase in aspect ratio;

iv) The degree of fibre alignmentwith stress direction.

Investigations have shown that with higher percentages of fibres, higher strengths are possible but with a decrease in workability.

Fibres currently being used in concrete and cement can be divided into two main groups; those with moduli lower than the cement matrix, such as cellulose, nylon and polypropylene and those with higher moduli such as asbestos, glass, steel, carbon and kevlar. The first group is capable of large energy-absorption characteristics. They give a good resistance and toughness to impact and explosive loading, but they do not lead to any significant strength improvements, whereas the second group impart characteristics of strength and stiffness and to varying degrees, dynamic properties.

Generally the addition of fibres improves the following properties:

i) Flexural strength;

ii) Crack resistance and ductility;

iii) Fracture toughness;

iv) Fatigue;

v) Fire resistance.

There is an infinite number of combinations of fibre variables such as length, diameter, shape and percentage by volume, which are possible within the limits set by the difficulties encountered in conventional mixing techniques. The higher the amount of small particle size in the matrix, the more fibres can be included in the composite. The distribution of the fibres is also affected by the particle sizes. Pulverised fuel ash or limestone dust has been added to provide the neccesary fine material.

Fibre reinforced concrete has been used in many applications such as pavements, airfields, bridge deck, roads, precast structural components, all with steel fibres. Pipes and piles using polypropylene and formwork using glass fibre have also been used.

1.2 Scope of proposed research

Although fibres have been successfully employed for imparting strength, ductility and toughness to many materials over the past few decades. There were major limitations, such as price of raw materials and conversion to fine wire and the inadequate bond strength inherent with highly polished, lubricated surfaces. In this research Arjex melt extract steel fibres were used to overcome the aforementioned limitations. They are manufactured by spinning a disc with a notched and multi-edged surface so that it just comes into contact with molten metal (the full process will be discussed in chapter two). Since they are stainless, they were applied in this investigation for high strength, durable fibre reinforcement in thin sheets instead of glass reinforcement. Their use in thin sheets was also regarded as an alternative to the health hazards associated with asbestos.

Having a lower aspect ratio (length/"diameter") they tend to be more workable and in this investigation an attempt was made to establish design information relating workability to the flexural strengths.

In the middle of the investigation a small quantity of raw mild steel fibres made from scrap material and named D-form , so-called because of their shape, were received from America. They were used on a small scale to test their workabilities and strengths. I used them for crack control in order to compare them with the melt extract steel fibres used by another student.

Finally an attempt was made to investigate the workability and flexural strengths and their use in thin sheets.

CHAPTER TWO : FIBRES FOR CONCRETE AND CEMENT

2.1 Introduction

Concrete, by virtue of its low cost, its easy availability, its relatively simple process technology, its good compressive strength and durability under widely varying environmental conditions is regarded as one of the great materials for construction in our time. However, the strengthening of concrete by the inclusion of short pieces of steel not only improves most of the existing properties of concrete but it can be used for many new applications.

During the past twenty years the properties and potential applications of a variety of fibre reinforced cements and concrete have been extensively studied throughout the world.

2.2 Materials used for fibre reinforcement

Fibres have been produced from a wide range of materials. These include the following types of fibres:

2.21 Asbestos fibres

Asbestos is a general name for several varieties of naturally occuring crystalline fibrous silicate minerals. It has been combined with cement to produce a wide range of thin sheet products since the turn of the century.It has also been used for cladding and roof sheeting, pipemaking, etc... Exposure to asbestos fibres can be injurious to health because it causes illnesses such as asbestosis and bronchial cancers.

A great deal is known about the long term durability of this material.[2,3]

2.22 Glass fibre

It can be produced with very high strength and elastic properties. The material is not normally alkali-resistant and is thus most suitable as a reinforcement material for gypsum and high-alumina cement, but fibres of special glass that are supposedly sufficiently alkali-resistant[4], for use with ordinary Portland cement have now been developed.

Glass fibres have been used for several years for the production of components, which have included cladding panels, heating ducts, precast chimney sections and boat hulls.

2.23 Carbon fibres

Carbon fibres are produced by carbonisation of suitable organic fibres at high temperatures. The texture of carbon fibres allows them to develop good frictional bond with the matrix.The fibres are inert to most chemicals but show anistropy in physical properties such as thermal expansion. Their cost is very high in comparison with the other types of fibres.

2.24 Polypropylene fibres

Polypropylene offered the textile industry a potentially low-priced polymer. The addition of the polypropylene fibres in a cementitious matrix improves particularly its impact resistance[5,6]. Due to the latter property, new products within the range of piling are being developed. Examples of polypropylene composites are thin section coatings to polystyrene block floation units, a limited range of precast units for pipe supports and bases for greenhouses.

2.25 Metal fibres

Metal fibres can be made of steel or steel alloys. However, taking into account the cost, stiffness and availability, only high tensile steel fibres are promising and widely used as reinforcement in cementitious matrices. Most steel fibres have the disadvantages of rust and stain in exposed situations. Some steel fibres are made from plain carbon steel, but fibres from 700 to 2,700 N/mm^2 are available. Special stainless steel fibres for refractory concrete subjected to elevated temperatures are also available. A "new" steel fibre known as the Arjex melt extract steel fibre has been produced at a cost significantly less than drawn wire carbon and stainless fibres. Since this research is based on these new fibres they will be discussed in greater detail in the next section. While the investigation using these Arjex fibres was underway, we received a limited quantity of a new mild steel fibre known as D-form due to their shape. These will be discussed more fully in chapter six.

Steel fibres are normally supplied from about 0.25mm to 0.75 mm in diameter and from 25mm to 50mm in length. The quantity that can be added to the mix and that can be uniformly distributed in the material greatly depends on the aspect ratio adopted.

2.26 Arjex melt extract steel fibres

The major limitations of the common fibres due to the price of raw materials and the high cost of conversion from rod to fine wire (these being particularly acute in the case of stainless steel intended for high temperature applications) and the inadequate bond strength inherent with highly polished, lubricated surfaces has led in 1974 the Batelle Corporation of Ohio to introduce melt extract steel fibres. Johnson and Nephew (Ambergate) Limited (U.K.) recently succeeded in developing commercial plant capable of producing a wide range of melt extract steel fibres of high quality and low cost.

i) The process

Basically, this involves bringing the periphery of a notched multi-edged spinning disc into contact with the surface of molten metal. On contact, the metal solidifies on, and adheres to, the rim of the disc and as a result is carried out of the melt. The rapidly cooling fibres then release themselves and are projected away from the disc. Fibre length and cross-sectional area are dictated by the spacing of the notches around the periphery of the wheel and the depth of immersion of the spinning edge, respectively (See plate 1).

ii) Benefits

The melt extract steel fibres are economical, since they make use of inexpensive raw materials. Their production satisfies the environmentalists because scrap metal can be re-cycled in the process.

Their novel "dished" cross sectional shape (See plate 2) provides a higher surface area for chemical bonding. The existance of irregular surface texture offers better grip for mechanical bonding and the absence of surface lubricants enables intimate contact between fibre and matrix.

They are more workable than their inferior drawn wire contem-

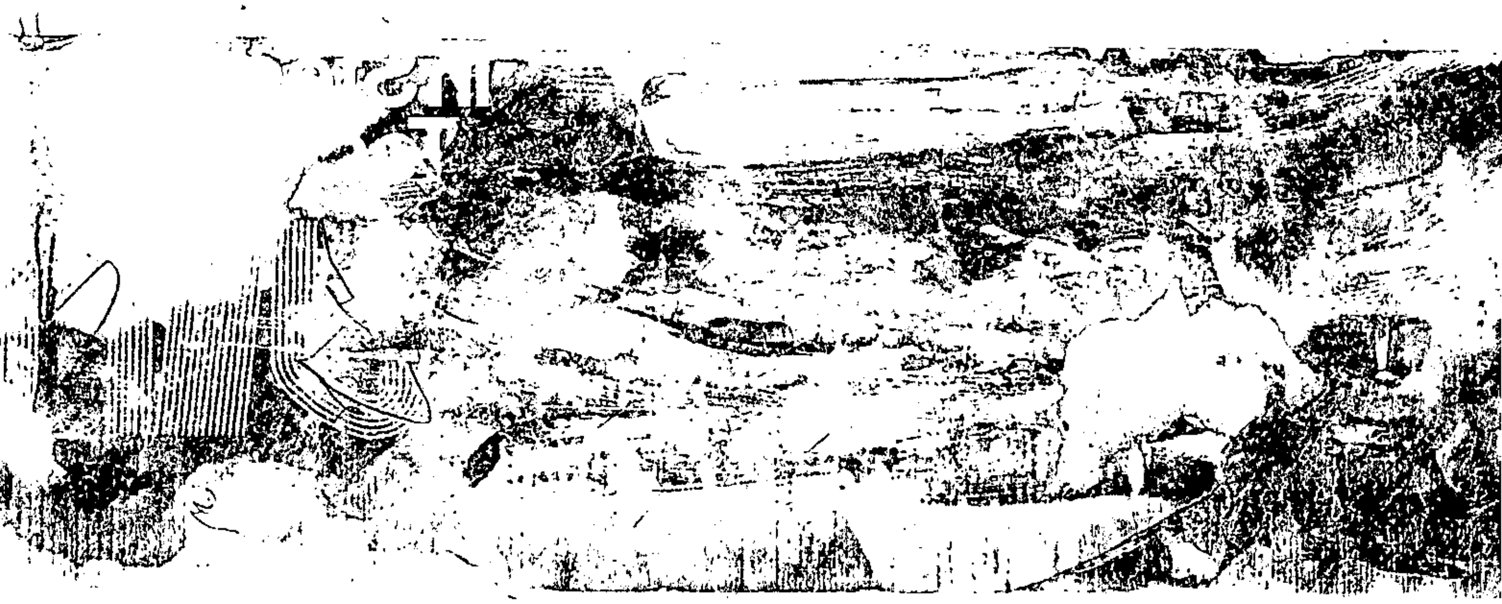


Plate:2 The melt extract fibres with their surface texture and "dished" cross section poraries since fibres having lower aspect ratios (length/"diameters") can achieve the same degree of anchorage due to the high area and its texture they provide for bonding (See plate 2).

Finally, one of their benefits is their inexpensive stainless nature which can be applied where the avoidance of surface staining is important.

iii) Fibre size and composition

The melt extract steel fibres are available in a wide range of "diameters" and lengths because of the nature of the manufacturing process, which means that fibres of any desired composition could be made from either carbon or stainless steels or nickel/chrome alloys for high temperature applications.

iv) Applications

Melt extract steel fibres are suitable for most applications where high strength, low cost and durable fibre reinforcement is required. The fine stainless fibres are suited for incorporation into thin sheet products, where they offer freedom from the time dependent strength and ductility losses associated with glass reinforced cements and the health hazards allied with the inhalation of asbestos.

2.3 Historical development

The experiments for strengthening concrete by the inclusion of short fibres were carried out by Porter[7] in 1910 and he concluded that the inclusion of cut nails into concrete increases the tensile and crushing strength of concrete.

In 1914, a patent was taken out by William Fickley[8] for the inclusion of various tortuous shaped pieces of metal reinforcement into concrete. The toughness and wearing resistance were increased but there were no improvements in the tensile and compressive strength of concrete.

In 1938 a patent was taken out by Nicolas Zitkevic[9] in which the first claims were made for an increase in the tensile, compressive and shearing strength of concrete by the inclusion of steel wire.

Very little further advance was made in the development or application of the material until the early 1960's when patents were taken out, both in Britain and the United States by the "Batelle Development Corporation"[10]. The claims were based on theoretical and experimental results obtained by Professor J.P. Romualdi. By the inclusion of steel fibres there was a reduction in the formation and propogation of cracks, reduced surface spalling and cracking under sudden application of heat and high energy absorption.

In 1963, two papers were published by Romualdi and Batson[11,12] in which details were given of the theoretical analysis upon which claims made in the Batelle patents were founded together with experimental data obtained from bending tests.

The basic concept of steel fibre reinforced concrete proposed by Romualdi was to assume a different mode of action of the steel from that of conventional reinforcement. A fracture arrest approach was adopted, which indicated that, for a given volume of steel added, the tensile strength of the composite would increase with decreasing wire diameter and hence wire spacing. It is important to note that this proposed type of behaviour does not comply with normal reinforcement concrete theory which does not predict any change in strength of the composite for a constant volume of steel and that the steel is present within the concrete to carry the tensile stresses rather than to prevent or retard cracking.

In 1964, a paper was published by Romualdi and Mandel[13] with results in flexural and cylinder splitting tests which confirmed the theoretical predictions regarding the effects of fibre spacing.

In 1965 and 1968, two papers were published by Romualdi[14], Romualdi Ramey and Sanday[15] which contained a repetition of that shown in the earlier papers.

In 1967 a further patent was taken out by the "Batelle Development Corporation"[16] for fibre reinforced concrete. The claims were for a composite construction for covering substratum comprising of alternative layers of unreinforced and fibre reinforced concrete. The intention of this was to reduce the cost of layering a pavement.

Another patent for fibre reinforced concrete was taken out by the "Batelle Development Corporation" in 1969.[17]

The first published objections were made to Romualdi's spacing concept in 1969. Romualdi's original work appeared to substantiate his theory but work by Shah and Rangan[18] has shown that fibre spacing alone has little effect on tensile strength. They observed improvement in ductility for fibre concrete but the effect of wire spacing was considerably less than predicted by Romualdi and

Mandel.

In 1970 and 1971 two further papers were published by Shah and Rangan[19,20] but they contained conclusions drawn from their original report in 1969.[18]

The reinforcing action of fibres was analytically predicted by Shah[20] and Mangat[21] and others by using the composite materials approach. The effective wire spacing in fibre reinforced concrete is very important, in view of the strong dependance of tensile strength on wire spacing. Kar and Pal[22] calculated the effective fibre spacing as follows:

$$Se = 8.85\ d. \sqrt{\frac{1}{Pn\ \frac{L}{Kd}\left(1 - \frac{L}{3Kd}\right)}}$$

where Pn = Bond efficiency in which P = fibre percentage (by volume);

L = Half the length of fibre;

d = "Diameter" of fibre;

K = As shown in Fig. 2.1.

There are many other papers written about the fibre reinforced concrete since the 1960's. One of the major publications was a Ph.D. thesis by John Edgington.[23]

He has found that the onset of cracking, the elastic moduli, creep and shrinkage remain, for practical purposes, unchanged by fibre addition. He claims that the addition of fibres gives only marginal increases in compressive, torsional and tensile strength whereas the largest increases in excess of 200 per cent were attained in flexural strength. He has shown that the effect of

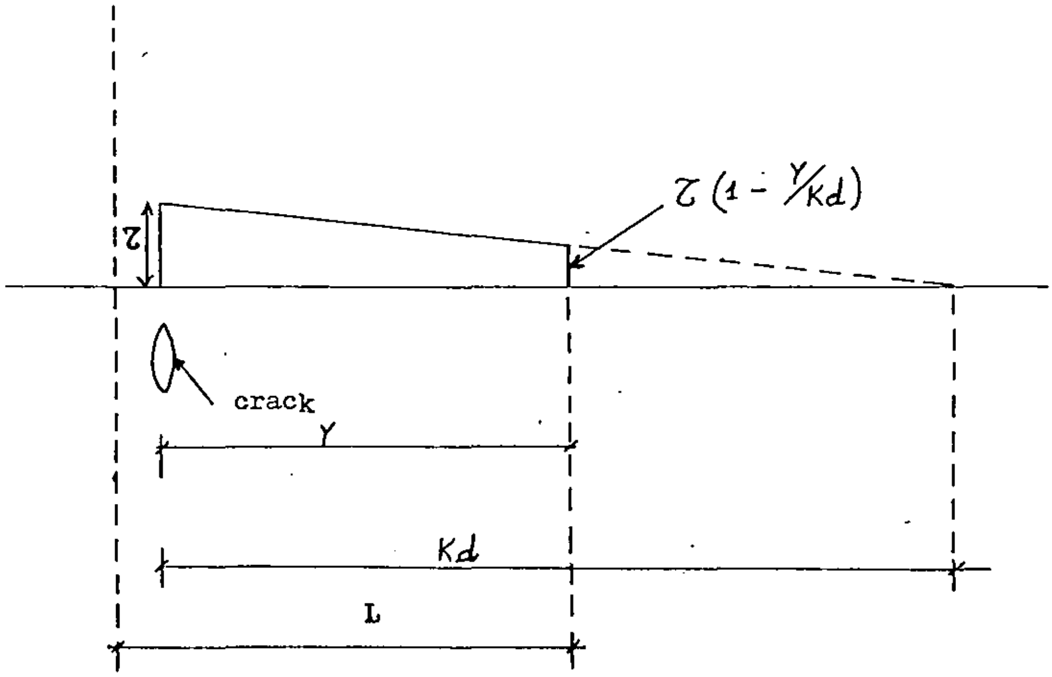


Fig. 2.1: Idealized bond stress distribution along the length of the fibres.

fibre spacing is negligible in direct tensile strength which is the contrary of early authors. He has found that the greatest benefits produced by fibre addition were those of increased toughness and ductility. Five fold increases in impact toughness could be obtained using selected fibre types in volume concentrations of less than two per cent.

2.4 Spacing concept

A brief description is given here of Romualdi and Batson's[12] fibre spacing theory, its disadvantages, and Swany and Mangat's theory[21].

2.41 Romualdi and Batson's[12] theory

They suggested that fibres act as crack arrestors by producing plucking forces which tend to close the crack.

The mechanism proposed by Romualdi and Batson[12] is primarily based on a geometrical fibre spacing concept which establishes a relationship between the first crack tensile strength of the composite and fibre spacing. This mechanism predicts that the first crack strength is inversly proportional to fibre spacing for a given percentage of fibres.

The basis of this theoretical development is illustrated in Fig. 2.2. A side view of an internal crack is shown located between two fibres. Under conditions of gross stress the external strains in the vicinity of the crack tip, due the stress concentration, are larger than average strains. These strains ,however, are resisted by the stiffer fibres and a set of bond forces is created that act to reduce the magnitude of stresses at the crack tip. Under proper conditions of fibre spacing and diameter, we can then allow the material to experience a larger section stresses, before crack propagation commences at a local internal level. In Fig. 2.3 the theoretical result linking first crack propagation stress and fibre spacing is shown. [illegible] ...ease [illegible] of the [illegible] the [illegible] matrix [illegible] obtained.

The basic assumptions of spacing concept are:

i) The shear forces at the fibres-matrix interface are absent until the occurance of a crack when the additional concrete displacements caused by the extentional strains in the neighbourhood of the crack cause a distribution of shear forces along the wires that act close to the crack.

ii) The bond between the fibres and the matrix is intact.

The disadvantages of this theory are:

i) The first assumption is valid only for long continuous fibres where the shear stress distribution in the absence of a crack extends only up to half the critical length ($\frac{Lc}{2}$), from each end of the fibre thus leaving a major proportion of the fibre length free from any shear stresses. The value of Lc depends on, and , if bond failure occurs, will then represent the frictional force per unit area between matrix and fibre. This assumption is not valid for short fibres of length small than the critical Lc;

ii) The second assumption is not necessarily true for discrete fibres; this does not take into account the influence of the geometry of the fibre . Further , the application of linear elastic fracture mechan-

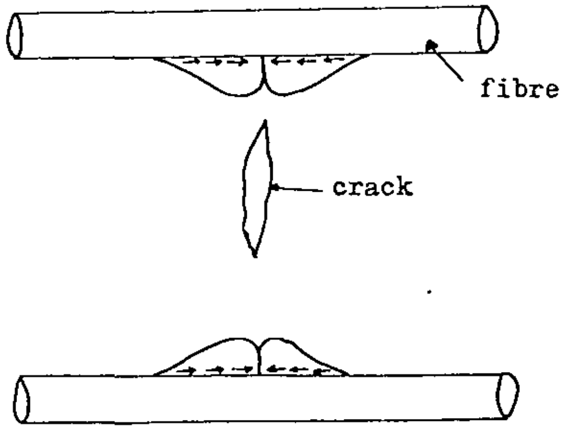


Fig.2.2 Section through crack and adjacent fibres (Romualdi and Batson)

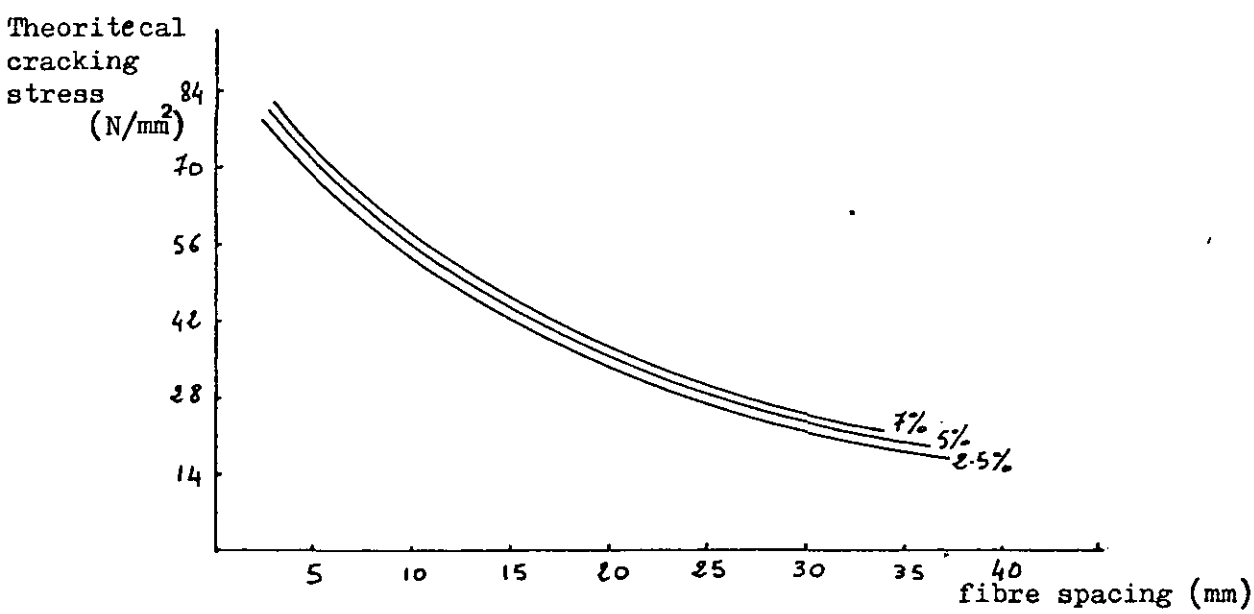


Fig.2.3 Cracking stress as a function of fibre spacing (Romualdi and Batson)

ics to cement, mortar and concrete is questionable;

iii) Probably the major drawback of the geometrical fibre spacing concept is that it is based on a direct tensile stress field, whereas the results used to prove the concept are based on flexural tests.

2.42 Swamy and Mangat's[21] theory

In the case of short, discontinuous fibres randomly orientated and uniformly dispersed in the matrix, there are three basic considerations related to the transfer of stress from matrix to fibre:

i) Critical fibre length on fibre transfer length;

ii) The fibre matrix interfacial bond; and

iii) The orientation factor for random fibres.

In this theory, new effective fibre spacing equations were derived. Bond deficiency was taken into account by introducing bond deficiency factors for both length and diameter of the fibres. An orientation factor was also introduced to take into account the randomness of the fibres.

The interfacial bond stresses of a steel fibre in a concrete matrix can be considered to consist of the following two parts:

i) The interfacial bond stress due to load transfer from matrix to fibres; and

ii) The interfacial bond due to the presence of a crack.

Romualdi and Batson[12] did not take into account the first bond stress; Kar and Pal did not either, although they considered a bond deficiency factor to fibre length alone. Swamy and Mangat[21] proposed a combined crack control composite materials approach to predict the first crack modulus of rupture and the ultimate modulus of rupture of fibre concrete. Cracks in the matrix occur when the composite strain exceeds the cracking strain of the matrix. On further loading the stiffer fibres act as crack arrestors ,analogous to coarse aggregates in plain concrete and a period of slow crack propagation with progressive debonding of fibres occurs. Finally, close to ultimate load, failure by fibre pull-out occurs with unstable crack propagation and interfacial bond attained the ultimate bond strength. Equations for first crack composite strength and for ultimate composite flexural strength were derived.

This mechanism of failure considered was justified from the excellent correlation of data from various sources.

2.5 Economics

The potential applications of fibre composites are in areas where the use of conventional concrete has severe limitations and in new areas where other materials give less than adequate performance.

The cost of fibres has now been drastically cut by the introduction of fibres such as melt extract steel fibres and D-form fibres. Even though, the comparison must not be drawn with plain or reinforced concrete on cost of materials alone. Fabrication and manufacturing costs must be taken into account. In this case material costs become a smaller part of the overall cost. Taking into account that the increasing demands on fibres will mean increasing production with possible cost decreases, fibre-concrete appears to be the material for the future.

2.6 Properties of steel fibre reinforced mortar and concrete in the fresh state

The addition of what amounts to an unusually high proportion of extremely elongated particles in the fresh state causes a stiffening of the mixture and a loss of workability. This loss of workability can be reversed to some extent by increasing the amount of mortar present in the concrete, reducing the maximum aggregate size, and increasing the water/cement ratio. However, if the percentage of fibres and their aspect ratio (length/"diameter"), exceed certain limits, it becomes impossible to achieve a level of workability adequate for placement by normal techniques. In addition, high aspect ratio fibres tend to form balls during the mixing process. The relatively cheap melt extract steel fibres ensure an adequate workability on the one hand and adequate strengthening on the other. An admixture (Conplast 337) was added to increase the strength by reducing the water/cement ratio without loss of workability. Since at the present time there is very limited information on the design of fibre reinforced concrete, an attempt was made in this investigation.

2.7 Properties in compression

Since the matrix is relatively strong in compression, and failure is initially due largely to breakdown at the aggregate paste interface, fibres have little effect on compressive strength. Documented increases[24,25,26] are negligible in most cases. Moreover, results for cubes and cylinders may be expected to differ because vibration tends to align the fibres perpendicular to the axis of loading for cylinders, where they could help to inhibit the lateral bursting which procedes failure, while tending to align them parallel to the axis of loading for cubes. Nevertheless, the toughness imparted by fibres in compression is useful in preventing sudden and explosive failure under normal static loading.

2.8 Properties in flexure

In contrast to the rather modest improvements in compression, improvements in flexure are more substantial. Researchers have sought to describe the behaviour of steel fibre reinforced concrete under static flexural loading using various parameters. Most clearly defined is the ultimate flexural strength or modulus of rupture. Flexural strength increases in relation to the product of fibre concentration and aspect ratio. However, very low fibre concentrations (less than 0.5 % by volume) and low aspect ratios (less than 50) are of negligible benefit. Toughness is a characteristic for which steel fibre reinforced concrete is particularly noted. Under static flexural loading, it may be defined as the area under the load-deflection curve or some portion thereof, that is as the work to cause complete failure or to reach a specified deflection.

2.9 Properties and uses of fibres in thin sheets

In 1904 asbestos was successfully added to cement to produce items such as industrial roofing. This was fairly cheap, sufficiently strong for practical uses , but possessed little impact resistance.Also , over the last ten years there has been increasing concern regarding the health hazards of handling asbestos.

Glass fibre reinforced cement in thin panels was first produced in the Soviet Union in the 1940's but the highly alkaline ordinary Portland cement (O.P.C.) had the tendancy to corrode the glass fibres. However, in 1970 Pilkington developed on alkali resistant fibre, knowm as Cem-Fil, by incorporating Zirconium Oxide into the conventional E-glass. Despite the inherently high alkali resistance of Cem-Fil glassfibre, some change in mechanical properties takes place with time as a result of both chemical and physical actions.

Hence, the investigation carried out on the melt extract steel fibres in thin sheets (6,8 and 12mm in thickness) was intended to replace asbestos and glassfibres.

So far little progress has been made in the use of steel fibres in thin sheets.

2.10 Crack control

One of the major problems with brittle cement matrices has always been the appearance of cracks, on the tensile side of the beams due to external loading.

Many investigators have demonstrated that glassfibres and asbestos could achieve a very smooth post-cracking tensile stress-strain curves.

Thus for the same reasons outlined in 2.9, melt extract steel fibres and mild D-form fibres were tried as crack arrestors. Thus as would be expected intuitively, high volumes of uniformly distributed fibres with high bond strength as in the case in the melt extract and D-form fibres are desirable.

SECTION ONE : WORKABILITY AND TESTING OF MELT EXTRACT STEEL FIBRE REINFORCED CONCRETE

CHAPTER THREE : PRODUCTION AND TESTING OF FIBRE REINFORCED CONCRETE

3.1 Introduction

Fibre reinforced concrete is a composite material made from at least five constituents, that is, fibre, cement, water, fine and coarse aggregate. The nature and proportions of each will constitute a variable which affects the strength and workability of the mix. It was for this reason that a certain number of mixes were chosen and a study was made to give information on the effect of melt extract steel fibres on workability and strength.

In this chapter a brief description is given of materials used for each mix, details of mix proportions, mixing procedure, workability testing and compressive and flexural testing.

3.2 Materials used for mix design

3.21 Fibres

In this investigation stainless melt extract steel fibres were used. They were the medium coarse, grade 410 and 25mm in length which were originally introduced by the "Batelle Corporation"of Ohio in 1974 (See plate 2).

3.22 Aggregates

The coarse aggregate used consisted of 10mm and 20mm natural river gravel. The fine aggregate was the natural river sand. All the aggregates were passed through the spiral elevator drier before being used.

3.23 Admixtures

Three admixtures were tried with the mix design 1:2:2 (cement: sand:10mm coarse aggregate) in order to determine the most suited to increase the strength without loss of workability (by reducing the water/cement ratio). The three admixtures were Conplast 211, Conplast 337 and Flocrete"N".

i) Conplast 211

Conplast 211 is a water reducing concrete admixture which complies with BS 5075:Part one:1974. It is based on selected stabilized, sugar reduced lignosulphates, and is supplied as a brown liquid instantly dispersable in water. When added to concrete mixes it enables the water content to perform more efficiently by causing the cement particles , which tend to agglomerate, to disperse and expose a larger surface area. The hydration reaction can then be produced more efficiently with less water. This effect is used to either improve workability, increase strength or reduce cement content of concrete.

ii) Conplast 337

Conplast 337 is a high performance plasticiser for concrete which complies with ASTM C-494 type A. It is based on a blend of specially selected organic polymers and supplied as a brown liquid which disperses instantly in water. It may be used to produce high workability concrete or to increase strength by enabling the water content to be substantially reduced.

iii) Flocrete "N"

Flocrete "N" is a water reducing admixture for concrete, conforming to B.S. 5075:1974. It is a brown liquid based on processed calcium lignosulphate. It does not contain calcium chloride which could be harmful to the durability of reinforced concrete.

Before deciding on the type of admixtures to be used for the investigations, all three admixtures were tried with 7 % by weight of fibre (percentage by weight $= \frac{\text{weight of fibres}}{\text{weight of matrix}} \times \frac{100}{1}$) in a 1 :2 : 2 mix. Thus the effect of the water cement ratio on V-B time and slump was investigated. It was found that for a V-B time just over one second and a slump of 75mm the value of the water cement ratio was 0.47 when using Conplast 211 or Flocrete "N" whereas it was only 0.414 in the case of Conplast 337. For the dosage of admixtures taken refer to Table 3.1.

Then from the table Conplast 337 is the most effective for the same degree of workability, the water cement ratio was the lowest, thus giving the highest strength.

The commercial viability of fibre composites is critically dependent on the cost of the fibre. The admixture to be used also excercises a controlling influence on the cost of the product because the matrix is cheap.

Thus, in order to choose the admixture to be used in relation to the price to be paid for the strength gained, the mix design 1 :2 : 2 was tried with the W/C ratios and the proportions of admixtures of Table 3.1. Three cubes (100mm by 100mm by 100mm) and three beams (500mm by 100mm by 100mm) were cast and tested after fourteen days (Table 3.2).

According to the results in Table 3.2, the use of Flocrete "N" or Conplast 211 give the same strength whereas the use of Conplast 337 increases the M.O.R. by 12.5 % and the compressive strength by 31 % over the use of the two other admixtures. However, the cost of Conplast 337 is higher than the other two admixtures. (Table 3.3).

With the mix design 1 :2 : 2, one cubic metre of concrete contains around nine bags of cement (50 kg per bag). Therefore, for one cubic metre of concrete we need 0.7 times nine litres of Conplast 337 or 0.14 times nine litres of Flocrete "N" (the use of Flocrete "N" is cheaper than the use of Conplast 211). Thus for each cubic metre of concrete we should pay an increase of £3.32 for using Conplast 337 instead of Flocrete "N" (it is one tenth of the price of the cement used). It is apparent from these calculations that for the strength gained, the use of Conplast 337 is better than the use of the two others. [illegible]

In order to see the strengths gained by using Conplast 337 and reducing the W/C ratios, tests were carried out at twenty eight days and the results are shown in Table 3.4.

Table 3.4 shows that it is worth using Conplast 337 for the strengths gained, particularly for the concrete mixes.(Conplast 337 was used at 0.85 L/50 kg cement which is the mean of the recommended values by the manufacturer).

However, the strengths can also be increased by the addition

Table 3.1 Effect of admixture type on workability

	SLUMP	V-B TIME(Sec)	W/C
FLOCRETE "N" 0.14 L/50kg of cement**	3" (75mm)	1.2	0.470
CONPLAST 211 0.14 L/50kg of cement**	3" (75mm)	1.4	0.470
CONPLAST 377 0.7 L/50kg of cement**	3" (75mm)	1.4	0.414

** The minimum dosage level recommended by the manufacturers.

Table 3.2 Effect of admixture type on strength

7 % by weight of fibres	FLOCRETE "N"	CONPLAST 221	CONPLAST 337
Mean M.O.R. (N/mm^2)	5.94	5.96	6.69
Mean compressive stress (N/mm^2)	52.01	52.53	68.63

Table 3.3 Prices of admixtures

	FLOCRETE "N"	CONPLAST 211	CONPLAST 337
Cost	£ 0.14/L*	£0.23/L**	£0.50/L**

* Cost given by the Cementation Chemical Limited (August 1980).

** Cost given by the FOSROC, CPB (U.K.),(August 1980).

of more fibres. Therefore an economic comparison between the addition of more fibres and the use of Conplast 337 was carried out and the results are shown below.

The increase in flexural strength between the beams OB75* and 7B75* tested at twenty eight days is of 15 % (no Conplast was used) whereas the increase in flexural strength between the beams OB75* with and without 0.85 L/50kg cement of Conplast when tested at twenty eight days was 17 %. A similar calculation as above shows that for roughly the same increase in flexural strength we pay £100 to achieve it by adding fibres(melt extract steel fibres cost £600/ton at the present time) compared with only £3.82 by using Conplast 337 in one cubic metre of concrete. These calculations thus confirm the advantage of using Conplast 337.

In the rest of the investigation the Conplast 337 was used at 0.85 L to every 50kg of cement. The range of mix proportions is given in Table 3.5.

If we refer to Table 3.5, mix A is a mortar mix, whilst mixes B,C and D are 10mm concrete mixes. D is rich in cement, whilst C contains more coarse aggregates than B and D. Mixes E and F are 20mm concrete, whilst E is rich in cement, F is rich in coarse aggregates.

For each mix I used the W/C ratios which give 75mm and 50mm slumps with 0 % fibres (See Table 3.6). Four, seven and ten per cent

* See Table 3.4.

Table 3.4 Use of Conplast 337 to increase strengths

*	Mean flexural strength of prisms (N/mm^2)		Mean compressive strength of cubes (N/mm^2)		% increase of flexural strength	% increase of compressive strengt
	Without Conplast 337	With Conplast 337	Without Conplast 337	With Conplast 337		
A75	7.36	7.82	46.56	66.75	6	43
75	5.75	7.09	48.79	72.65	23	49
75	6.13	7.05	42.87	53.34	15	24
75	7.01	8.28	65.54	87.17	18	33
75	6.32	7.80	61.55	73.30	23	29
75	5.49	6.53	55.33	73.78	19	33

* Percentage of fibres by weight of the matrix/mane of the mix(See Table 3.5)/slump in mm

Table 3.5 Mix proportions used for the investigation

MATRIX TYPE	Weight of mix constituents				MIX
	Cement O.P.C	Sand	10mm aggregate	20mm aggregate	
Mortar	1	2.4	—	—	A
10mm aggregate	1	2	2	—	B
	1	2	3	—	C
	1	1.5	1.5	—	D
20mm aggregate	1	1.5	0.5	1	E
	1	1.5	2.5*		F

* The proportion of the 20mm gravel is twice the proportion of the 10mm gravel

Table 3.6 Values of the water/cement ratios used in the mixes

/	W/C	Slump at 0 % fibre content
MIX A	0.3763	75mm
	0.36	50mm
MIX B	0.384	75mm
	0.36	50mm
MIX C	0.428	75mm
	0.408	50mm
MIX D	0.2971	75mm
	0.2857	50mm
MIX E	0.30	75mm
	0.2886	50mm
MIX F	0.3167	75mm
	0.3033	50mm

fibres by weight of matrix were then added to each mix. (For the mix A twelve per cent fibres by weight of matrix was also mixed.) With each percentage added the slump and V-B time were determined. (Chapter four).

Finally ordinary Portland cement was used in all mixes with tap water free from any deleterious substances.

3.3 Mixing procedure

Before deciding on the type of concrete mixer to use for the investigation, initial mixing trials were carried out using two types of pan mixer. The first was a liner cumflow mixer type O which had a capacity of 0.043 cubic metres, and a power driven rotating pan and paddle. The second was a cretangle mixer type E123 having a capacity of only 0.028 cubic metres in which the centre paddle was not power driven. The performance of the cumflow mixer was good for achieving uniform fibre distribution, whereas the cretangle mixer was virtually useless due to the accumulation of fibres around the scraper blades and paddle resulting in eventual seizure of the mixer for the mixes having seven per cent by weight of fibres or more. The sequence in which the various constituents of the mix were added into the mixer was irrelevant vis-a-vis the provision of the best uniform distribution.

I noticed that until twelve percent for the mortar mix and ten percent for the concrete mixes of fibres by weight of the matrix the melt extract steel fibres (grade 410- medium coarse and 25mm long) never ball. Due to the improved mixing characteristics of the melt extract fibres over their drawn wire contemporaries, it

(For the mixer used see plate: 3)

Plate:3 The liner cumflow mixer and the equipment used for the V-B and the slump tests was found unecessary to use a fibre dispenser when adding the fibres to the mix.

3.4 Mixing technique

The mixing technique adopted was as follows:

i) The aggregates, the sand, the cement and the fibres were poured carefully into the mixer and mixed for two minutes.

ii) The water and the Conplast 337 were added and mixed for a further two minutes.

3.5 Workability testing

To assess the effect of the melt extract steel fibre (grade 410-coarse-medium and 25mm long) percentages and aggregate parameters on workability, two tests were used: the slump and V-B tests (See plate 3). The equipment was that described in B.S. 1881 and the tests were carried out in the same manner described in the standard.

3.6 Compaction

The specimens were compacted using a laboratory vibrating table which had a vibration frequency of 50 Hz and a variable amplitude.

The steel moulds were placed unclamped on the vibrating table and were filled with fibre reinforced concrete until just level with the top of the mould. Additional material was being added continuously into the mould during compaction. The time needed for compaction was around four minutes.

3.7 Stripping and curing

The specimins were kept in their moulds for twenty four hours covered with polythene sheets. They were then demoulded and stored for twenty eight days in water tanks kept at 20° C.

3.8 Compressive and flexural testing

3.81 Compressive tests

These were carried out in a Denison T60C (See plate 4) at a loading range of 120 tons and at twelve per cent rate on 100mm by 100mm by 100mm cubes as described in B.S. 1881.

3.82 Flexural tests

These were carried out in the same machine, the Denison T60C on 500mm by 100mm by 100mm long specimens at the third load points on a span of 400mm. The rate and range chosen were specifically thirteen per cent and 3 tons (B.S. 1881).

Plate:4 Denison T60C (For the flexural and compressive tests)

CHAPTER FOUR : RESULTS OF THE WORKABILITY INVESTIGATION

The workability, compressive and flexural strengths of fibre composites are difficult to predict because of the large number of parameters involved. Apart from the water content, the major factors which influence significantly the workability are the aggregate content, the fibre geometry and the percentage of fibre content.If the concentration of fibres and their aspect ratio exceed certain limits, it becomes impossible to achieve a level of workability adequate for placement by normal techniques. In the hardened state, the application of load causes a transfer of stress from the matrix to the fibre by interfacial shear. This transfer of stress takes place before and after cracking of the matrix. Before cracking has started they modify the inherently brittle behaviour of the matrix. Hence, the bond strength is a critical factor. It was anticipated that the ragged shape of the melt extract steel fibres would give a good bond and that the problem associated with the workability would be overcome due to their aclaimed good workability, as was put forward by the manufacturer.

4.1 Slump and V-B time values

The values of the slump and V-B time related to fibre content are shown in Figures 4.1 - 4.12. Each curve is identified by the water/cement ratio used in the mix. The zero slump values are also plotted with their related fibre contents.

4.2 Compressive and flexural strengths

The relationships between composite strength and fibre concentration for each mix design and its water/cement ratio are

The effect of fibre weight contents on slump of O.P.C. + Sand (mix A)

MIX DESIGN:1:2.4 ; W/c= 0.3763

W/c= 0.36

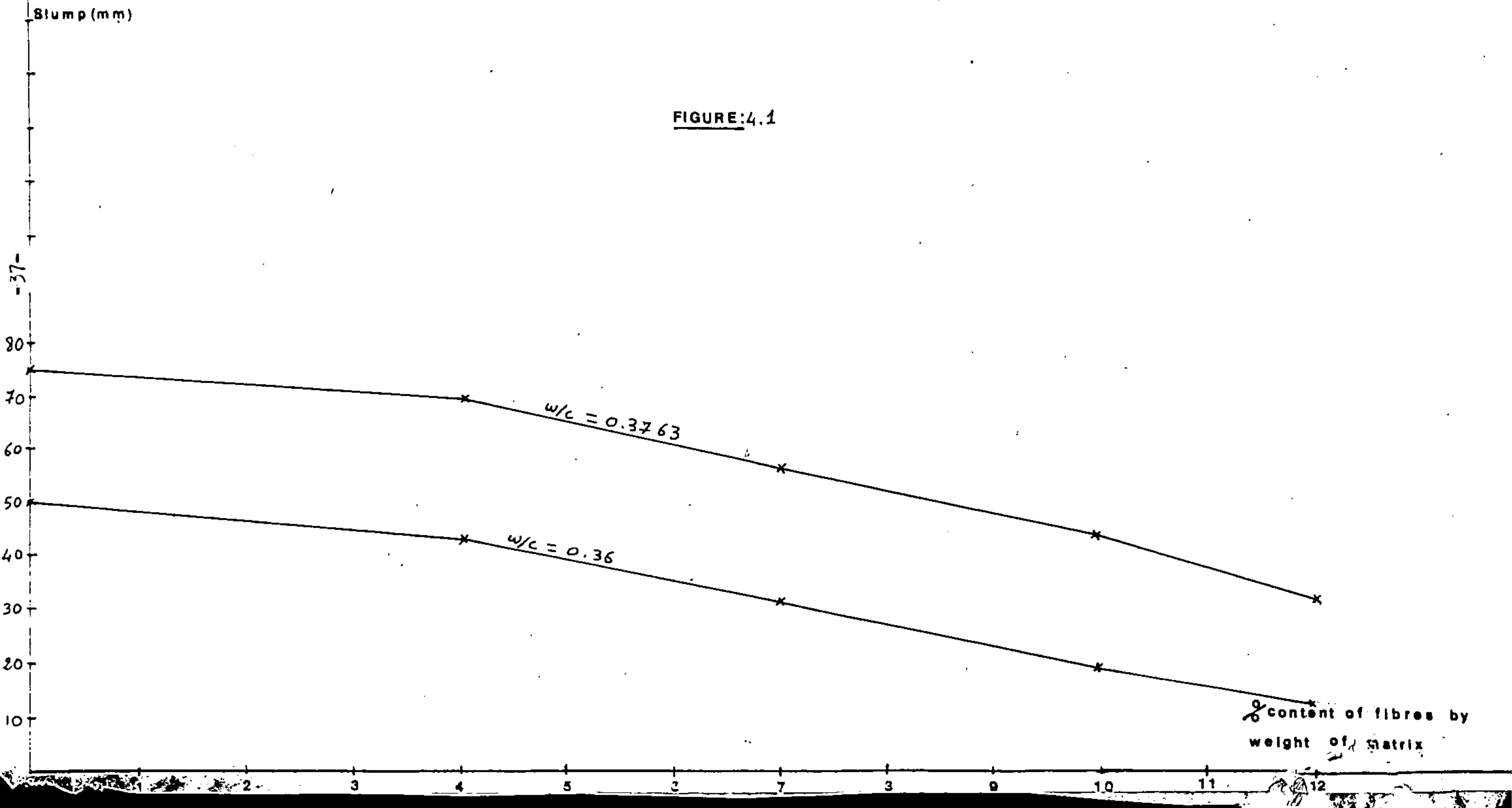
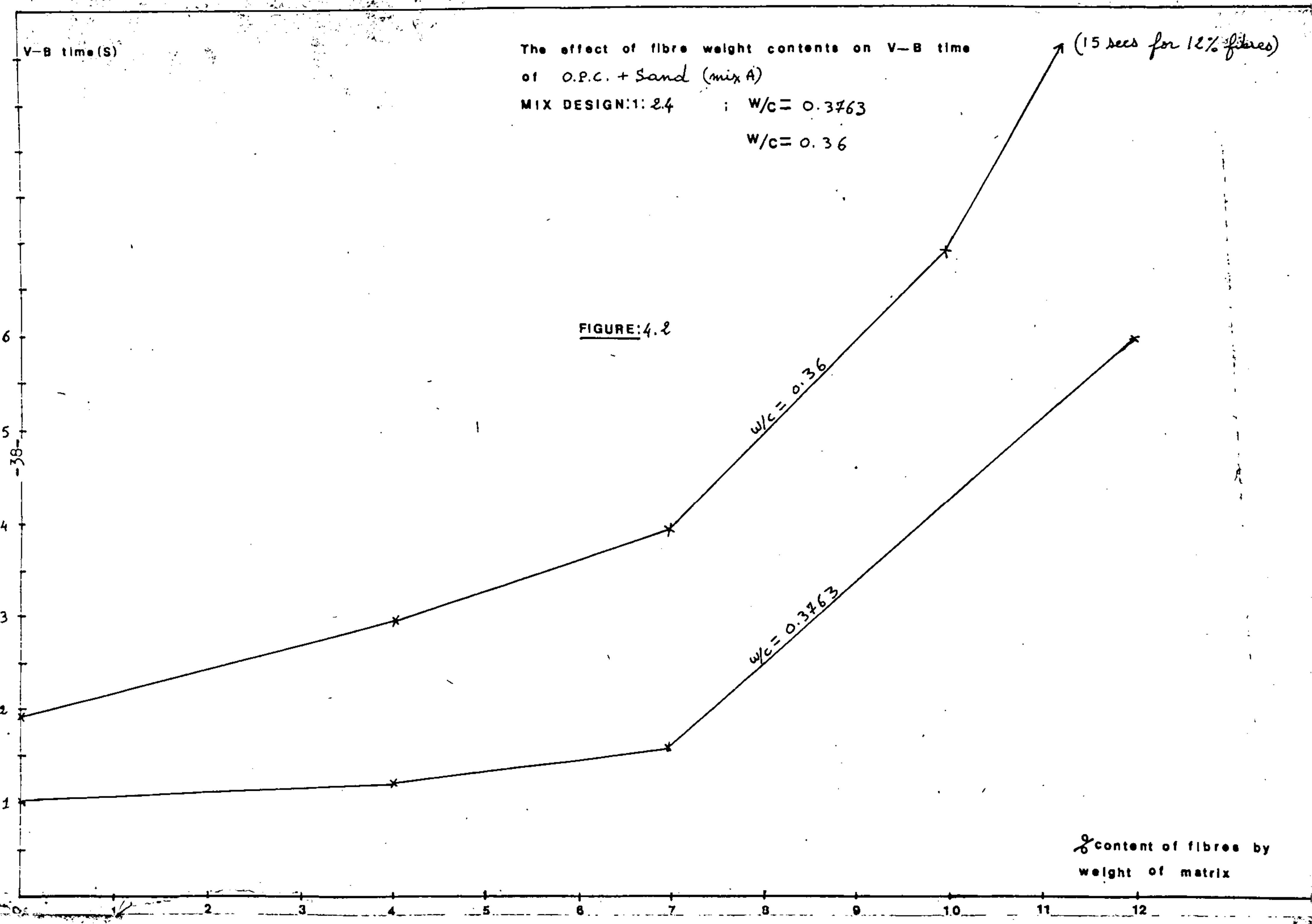


FIGURE:4.1

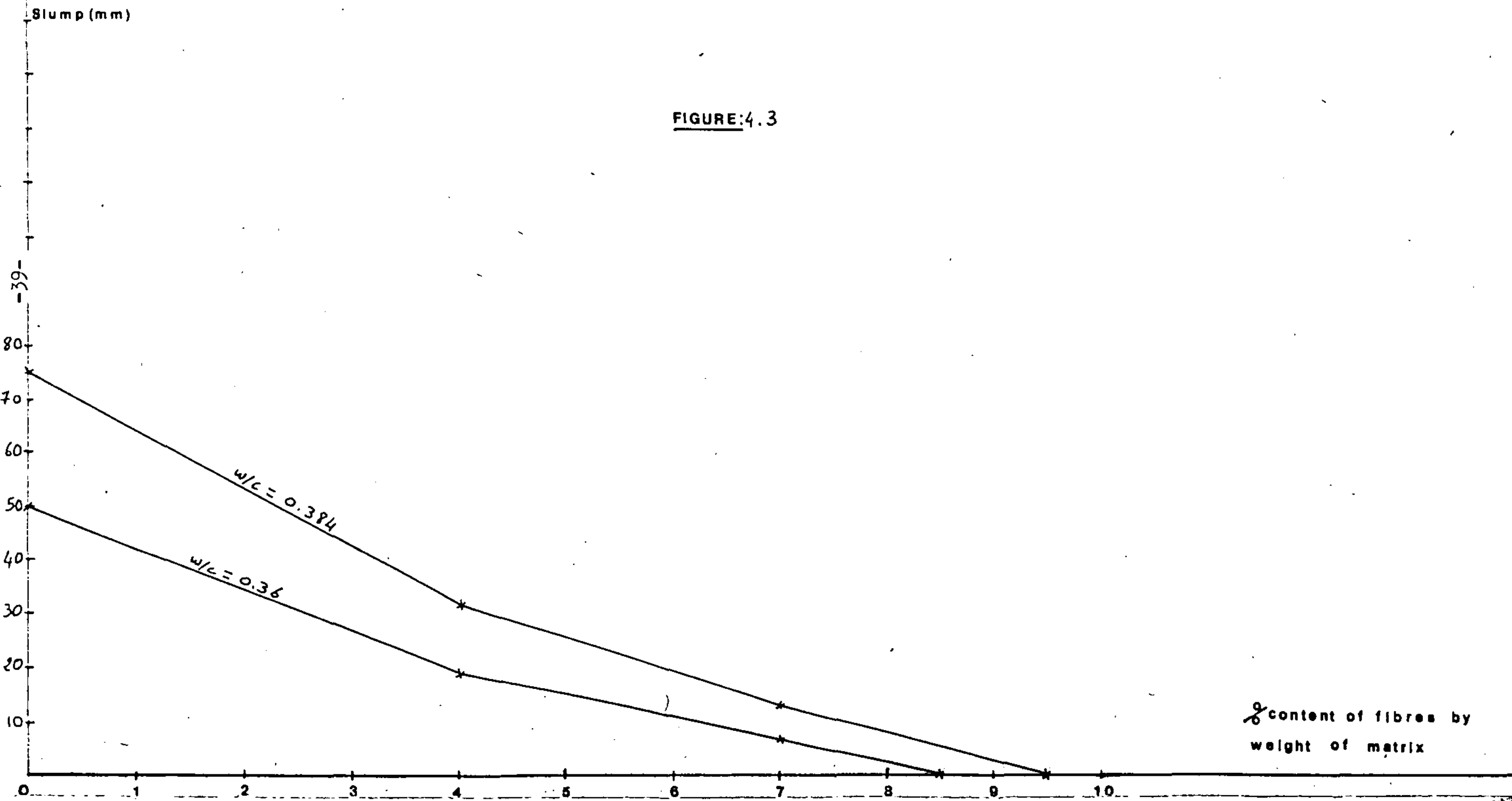

V-B time (S)
The effect of fibre weight contents on V-B time
of O.P.C. + Sand (mix A)
MIX DESIGN: 1: 2.4 ; W/c = 0.3763
W/c = 0.36
(15 secs for 12% fibres)
FIGURE: 4.2
w/c = 0.36
w/c = 0.3763
% content of fibres by weight of matrix
-38-

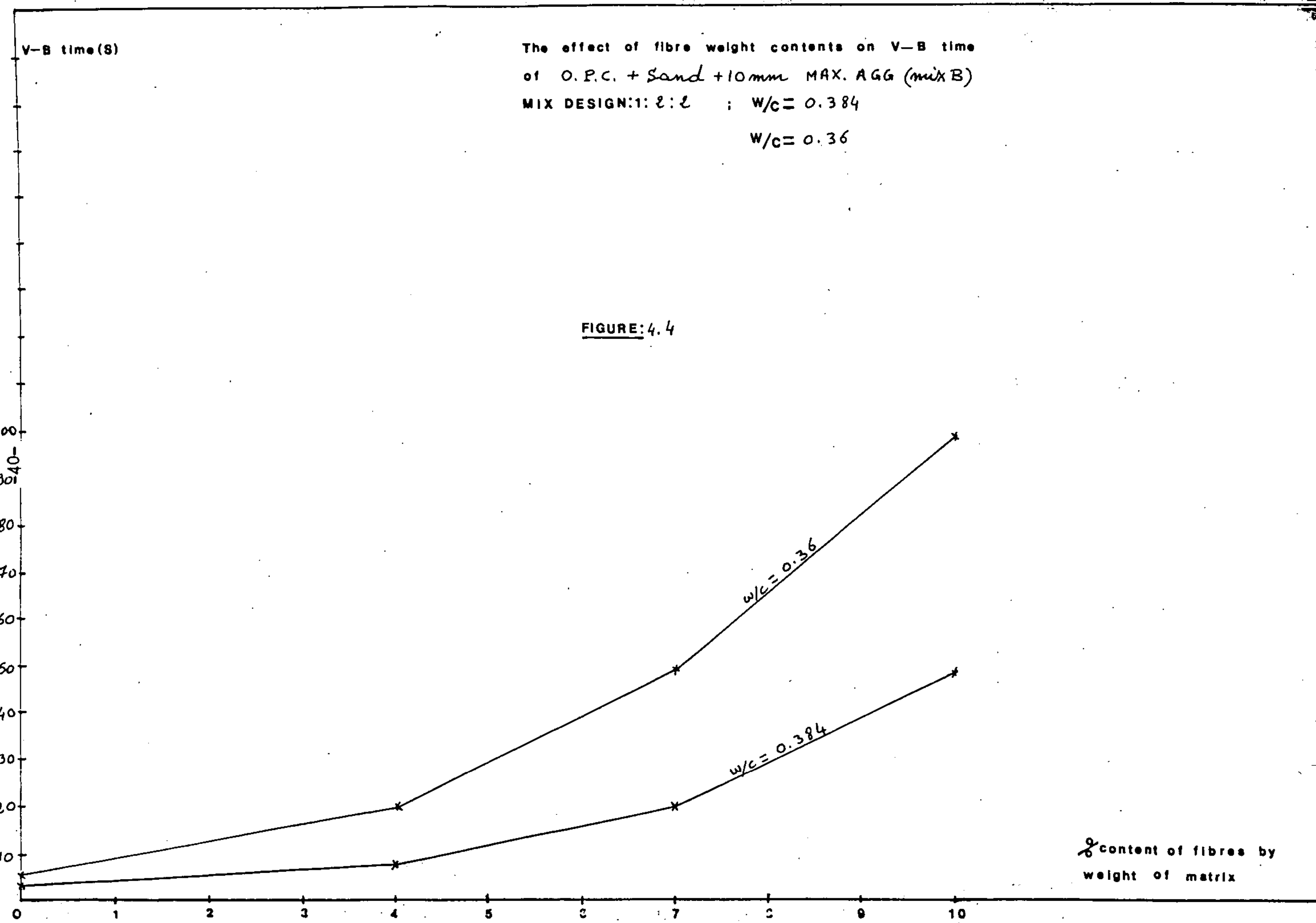
The effect of fibre weight contents on slump of O.P.C. + Sand + 10mm MAX AGG (mix B)

MIX DESIGN: 1:2:2 ; W/c = 0.384

W/c = 0.36

FIGURE: 4.3





The effect of fibre weight contents on V—B time of O.P.C. + Sand + 10mm MAX. AGG (mix B)
MIX DESIGN: 1: 2: 2 ; W/c = 0.384
W/c = 0.36

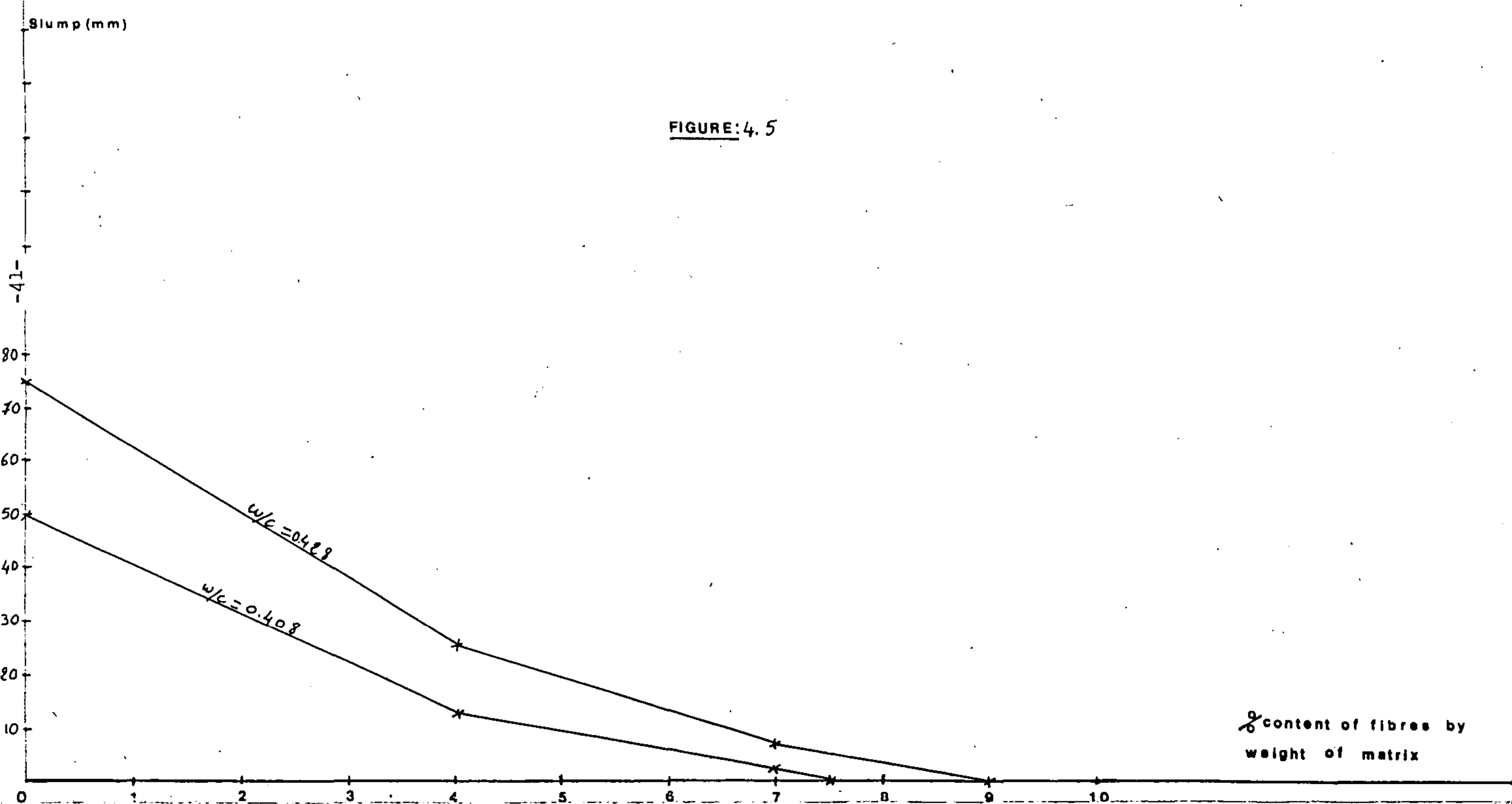
FIGURE: 4.4

The effect of fibre weight contents on slump of O.P.C. + Sand + 10mm MAX. AGG. (mixc)

MIX DESIGN: 1:2:3 ; W/C = 0.429

W/C = 0.408

FIGURE: 4.5



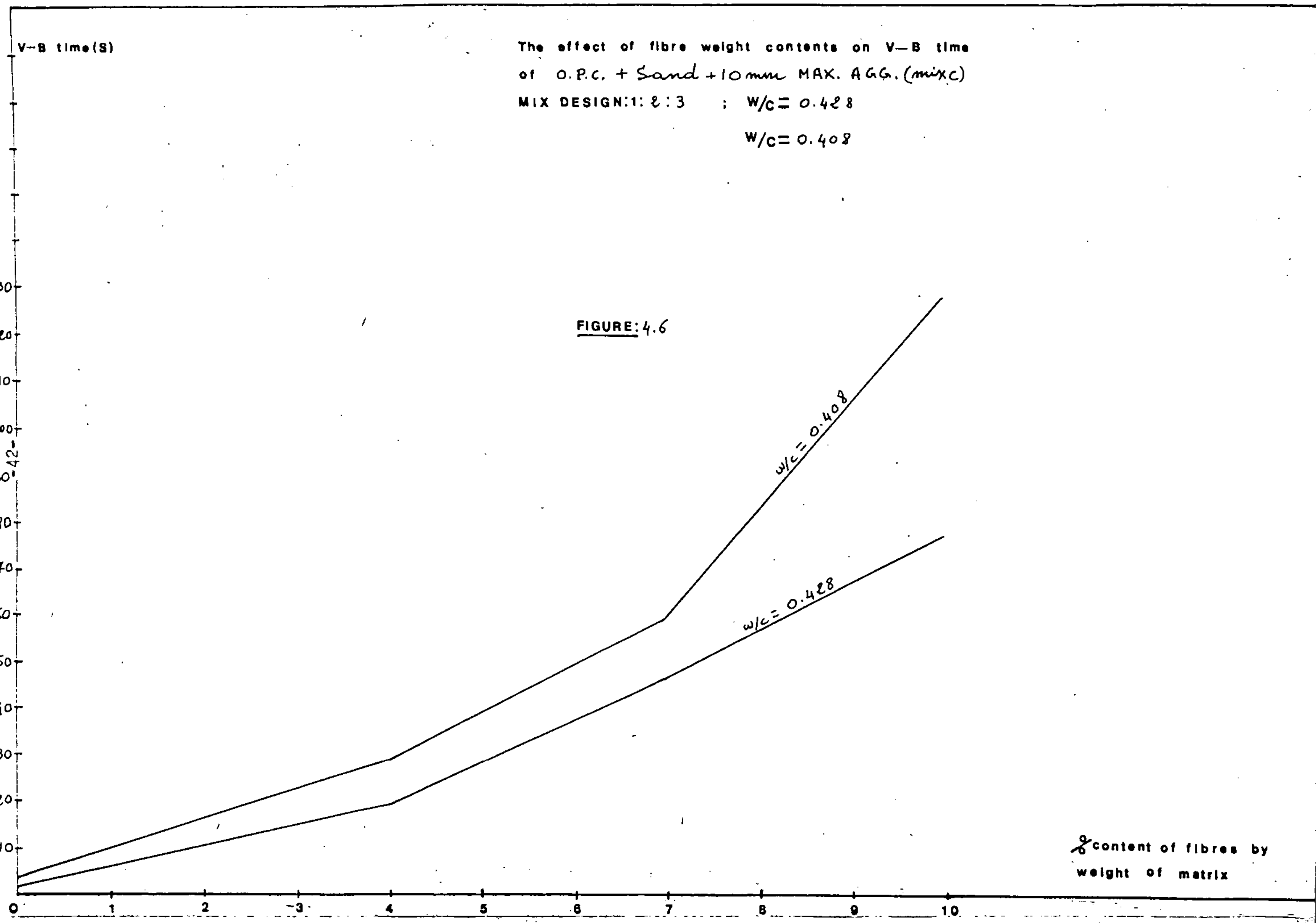

V–B time(S)
The effect of fibre weight contents on V—B time
of O.P.C. + Sand + 10mm MAX. AGG. (mix C)
MIX DESIGN: 1: 2 : 3 ; W/C = 0.428
W/C = 0.408
w/c = 0.408
w/c = 0.428
% content of fibres by weight of matrix
0
1
2
3
4
5
6
7
8
9
10

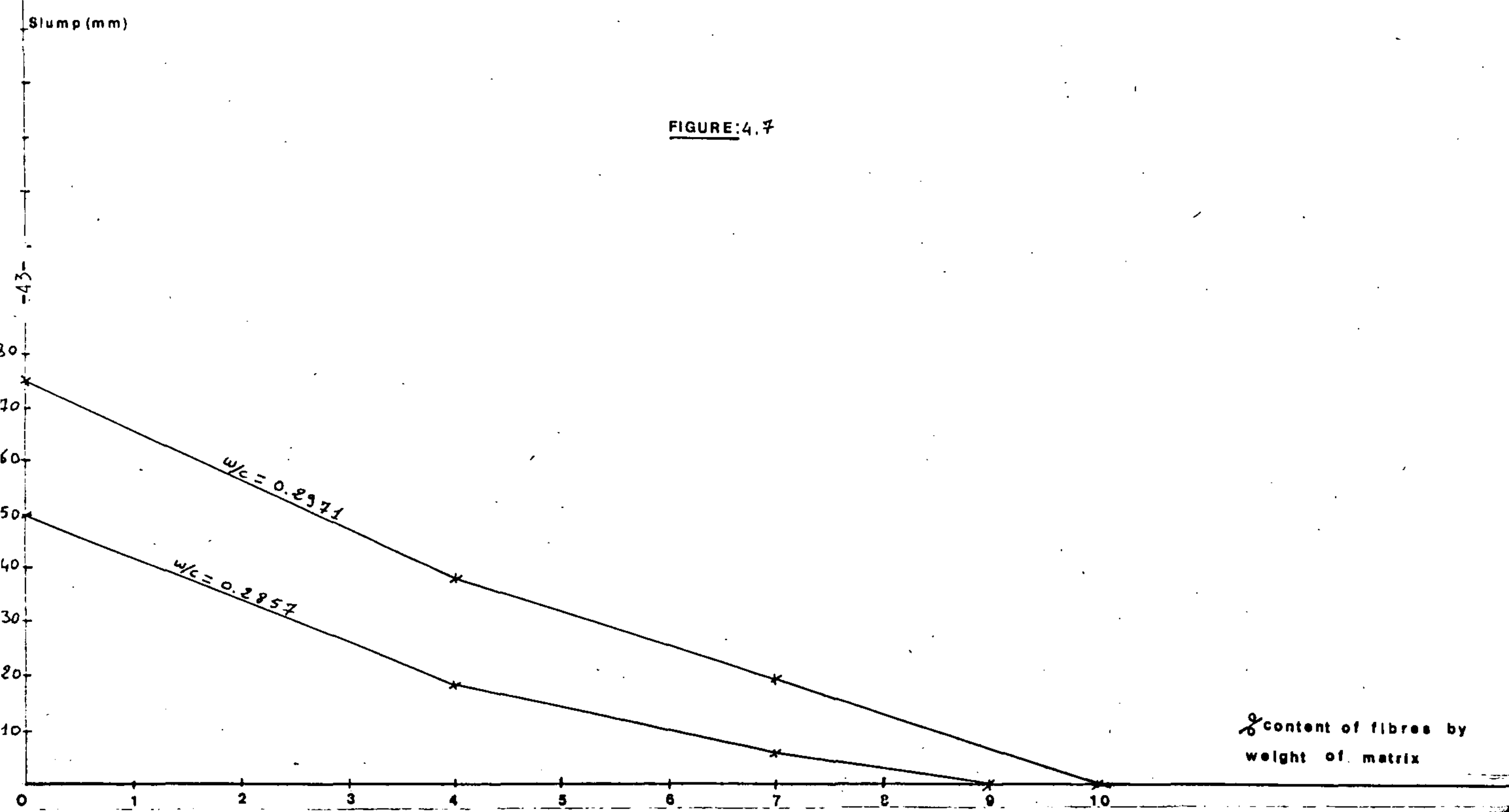
FIGURE: 4.6

The effect of fibre weight contents on slump of O.P.C. + Sand + 10mm MAX. AGG. (mix D)

MIX DESIGN: 1:1.5:1.5 ; W/c = 0.2971

W/c = 0.2857

FIGURE: 4.7



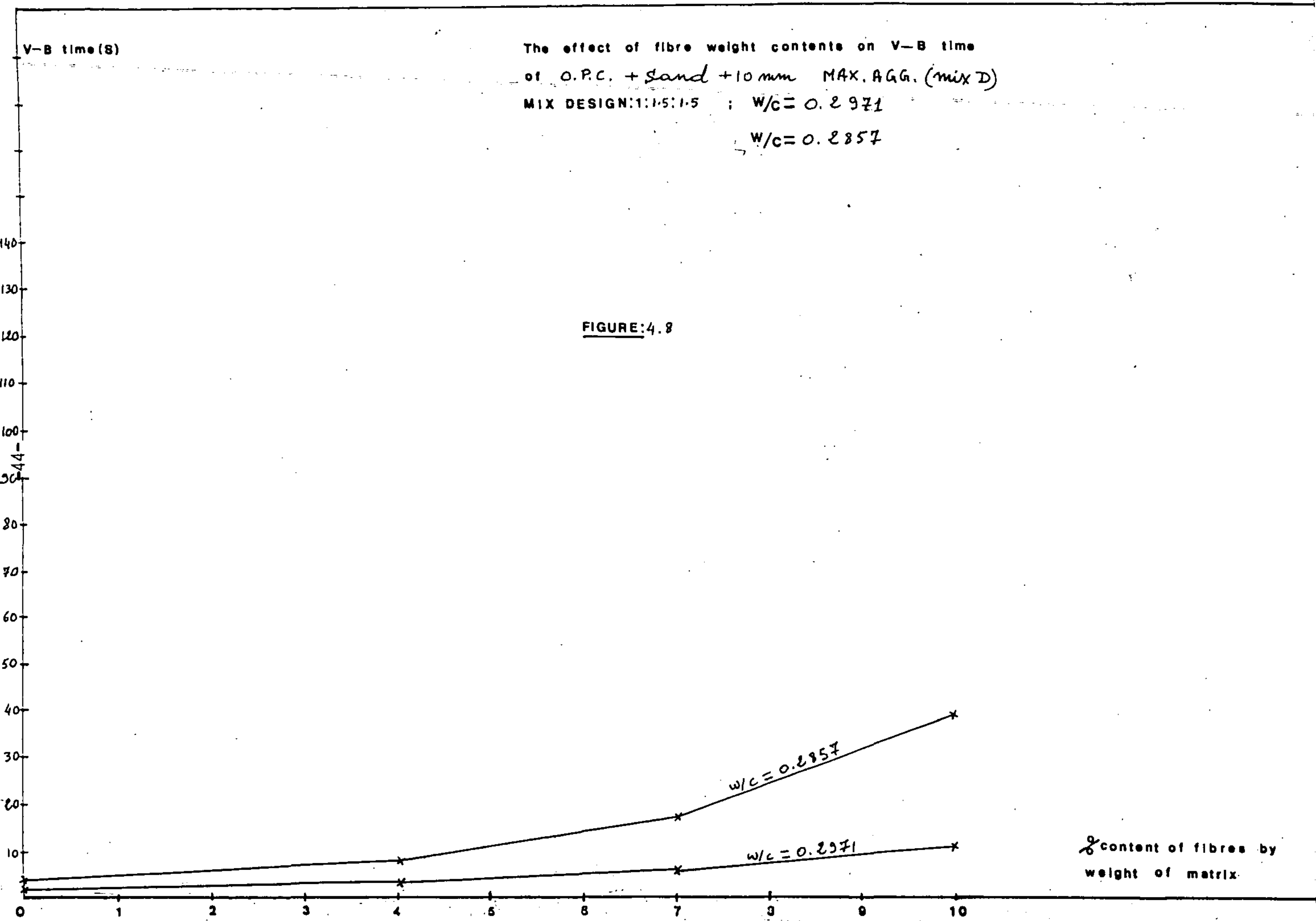

V-B time (S)
The effect of fibre weight contents on V-B time
of O.P.C. + Sand + 10 mm MAX. AGG. (mix D)
MIX DESIGN: 1:1·5:1·5 ; W/c = 0.2971
W/c = 0.2857
140
130
120
110
100
90
80
70
60
50
40
30
20
10
w/c = 0.2857
w/c = 0.2971
% content of fibres by weight of matrix
0
1
2
3
4
5
6
7
8
9
10

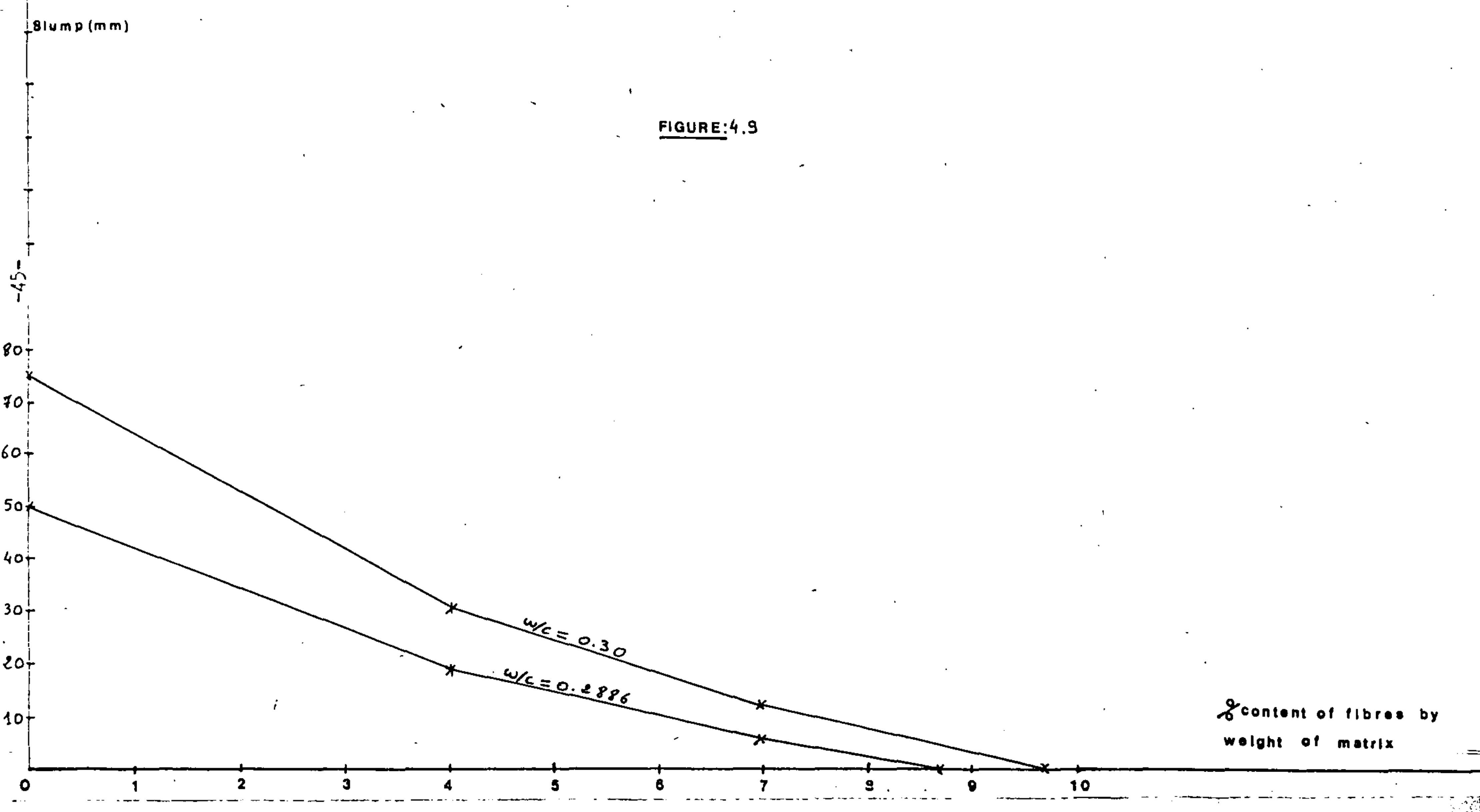
FIGURE: 4.8

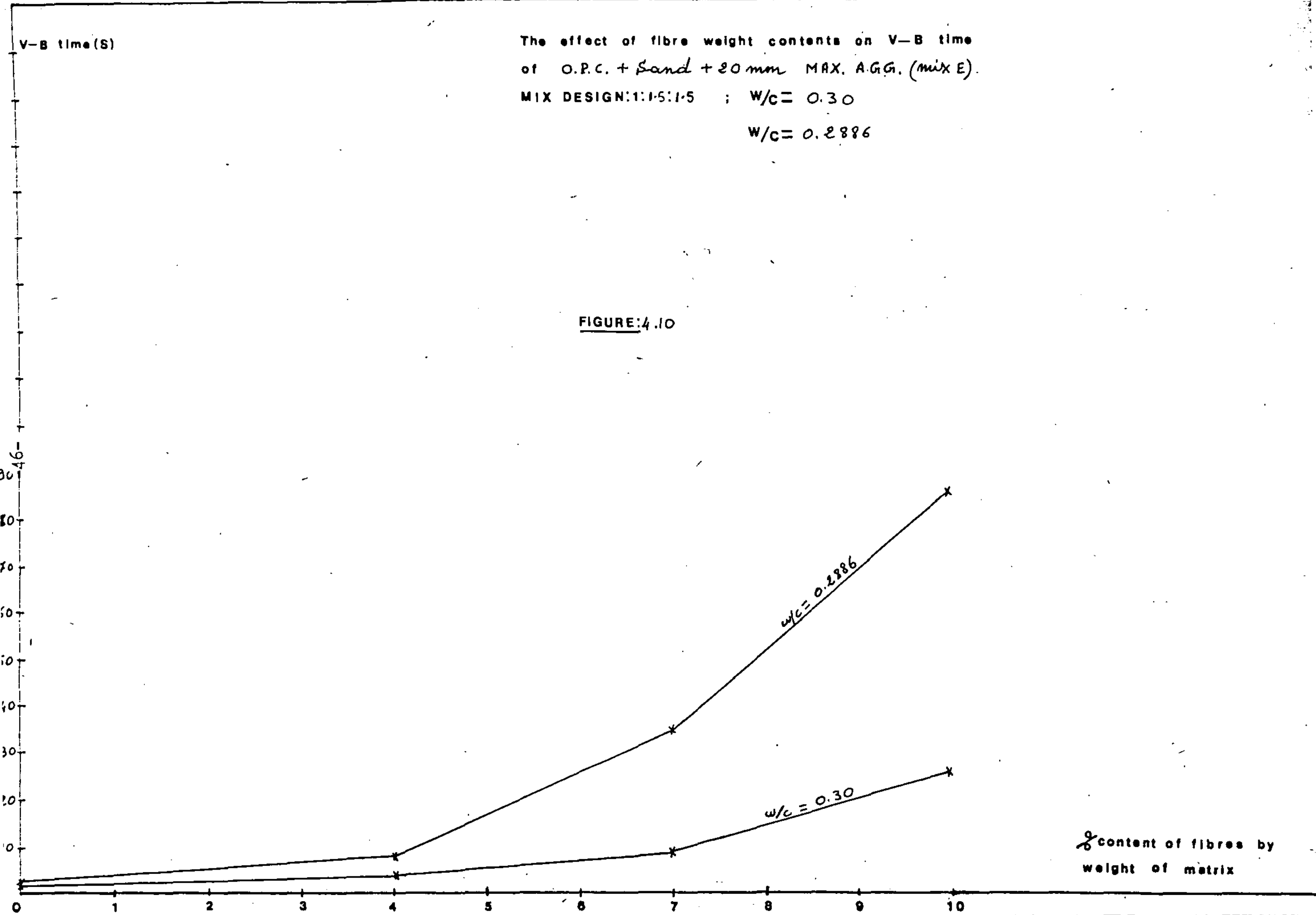
The effect of fibre weight contents on slump of O.P.C. + Sand + 20 mm MAX. AGG (mix E)

MIX DESIGN: 1:1.5:1.5 ; W/c = 0.30

W/c = 0.2886

FIGURE: 4.9





The effect of fibre weight contents on V-B time of O.P.C. + Sand + 20 mm MAX. A.G.G. (mix E).
MIX DESIGN: 1:1·5:1·5 ; W/c = 0.30
W/c = 0.2886

FIGURE: 4.10

The effect of fibre weight contents on slump
of O.P.C. + Sand + 20mm MAX. AGG. (mix F)
MIX DESIGN: 1:1.5:2.5 ; W/C = 0.3167
W/C = 0.3033

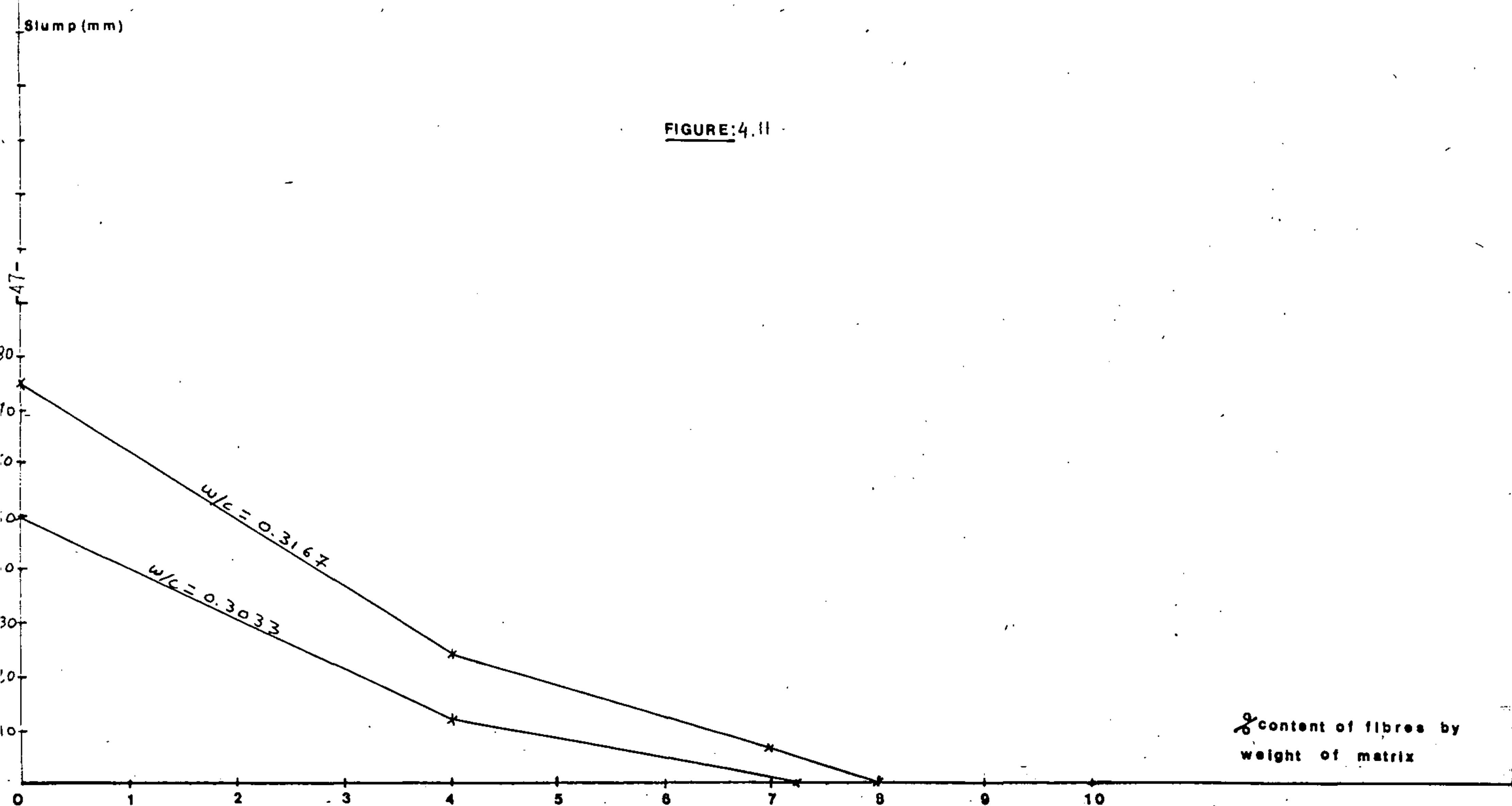
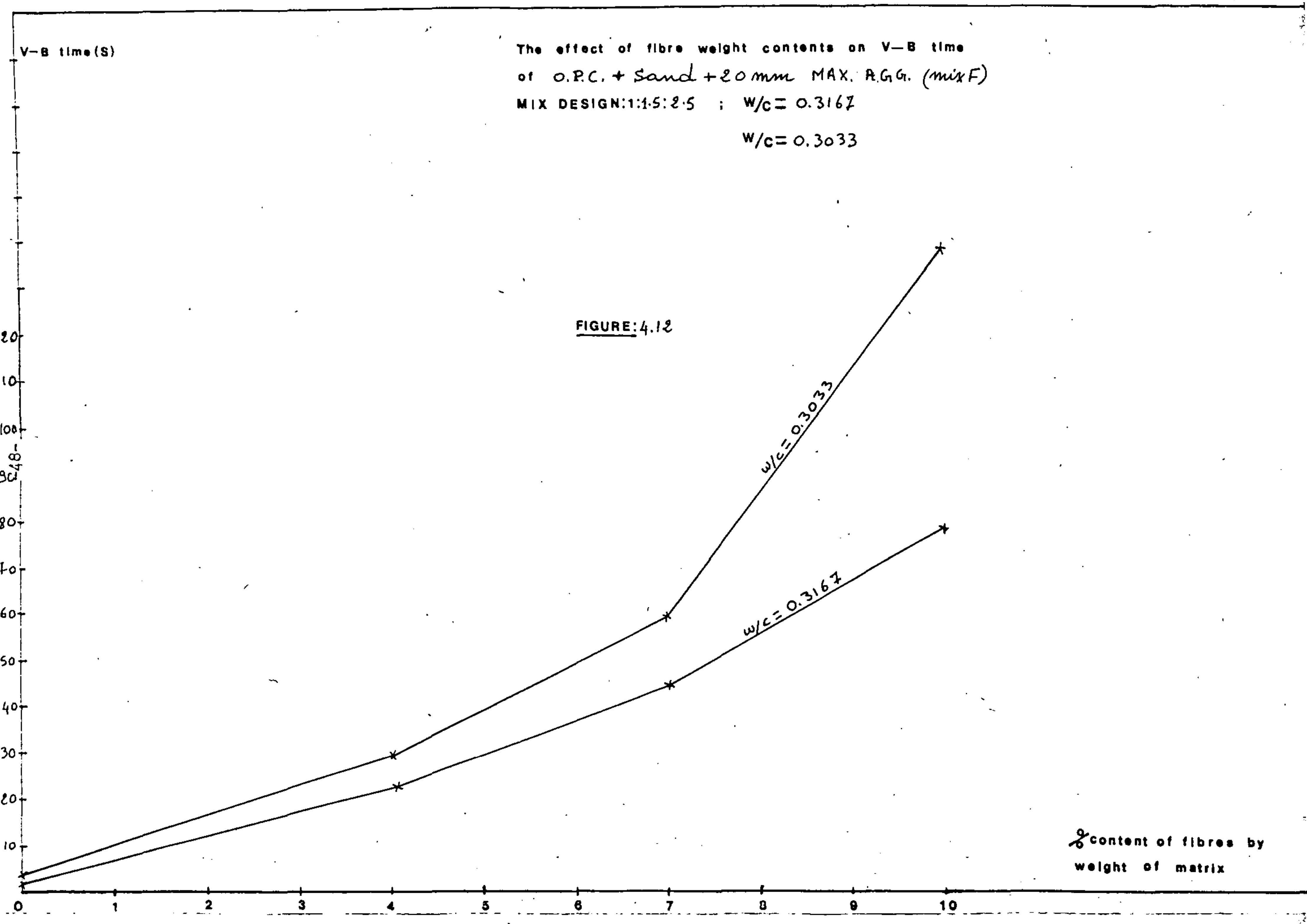


FIGURE: 4.11


The effect of fibre weight contents on V—B time
of O.P.C. + Sand + 20 mm MAX. A.G.G. (mix F)
MIX DESIGN: 1:1.5:2.5 ; W/c = 0.3167
W/c = 0.3033
FIGURE: 4.12
V—B time (S)
w/c = 0.3033
w/c = 0.3167
% content of fibres by weight of matrix
0
1
2
3
4
5
6
7
8
9
10
10
20
30
40
50
60
70
80
90
100
10
20

shown in Figures 4.13 - 4.24 for compressive strength, and in Figures 4.25 - 4.36 for flexure strength.

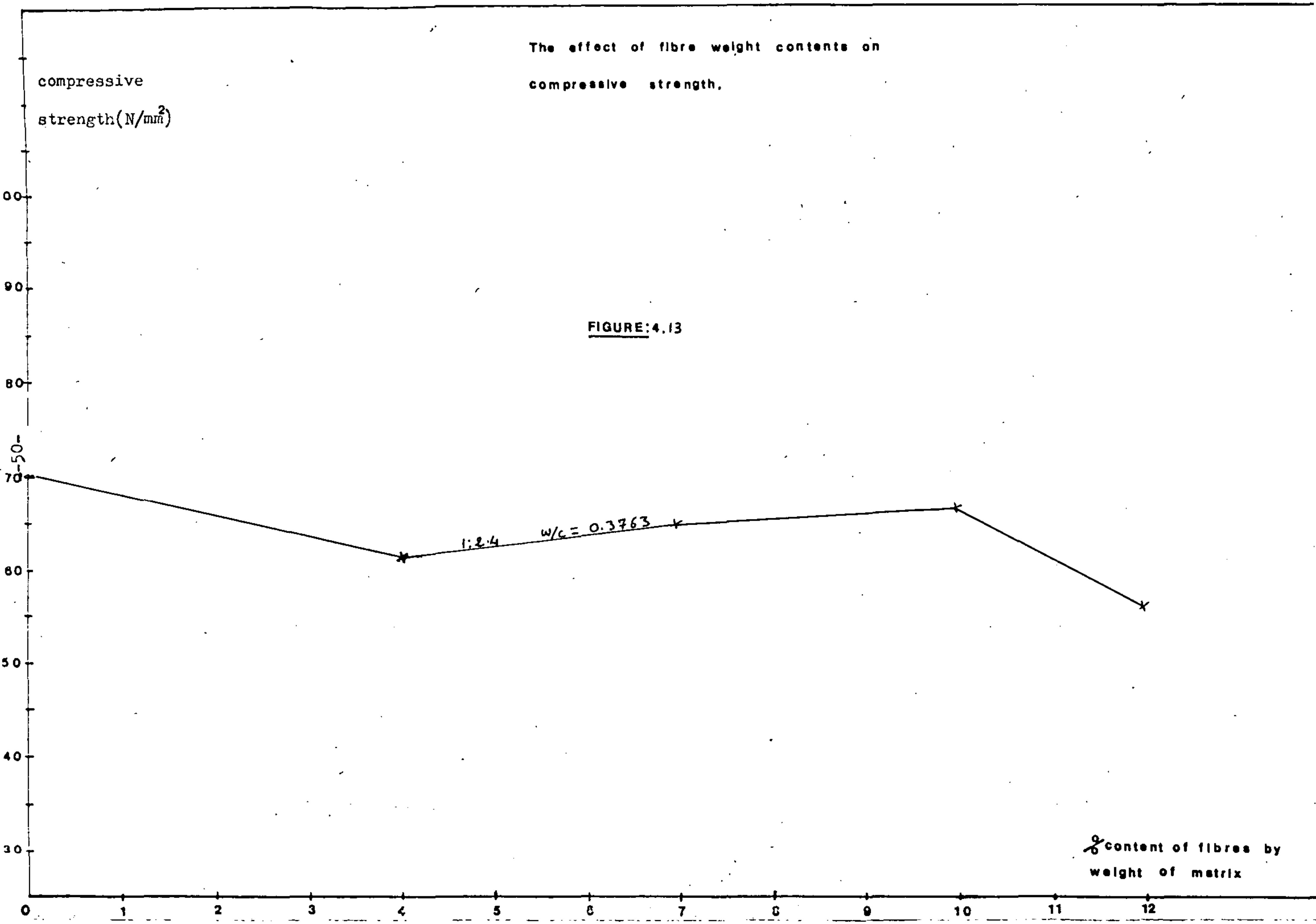
The strength of each composite was determined from three nominally identical specimens and the average values were joined by straight lines. The standard deviation, coefficient of variation and mean strengths for each composite are shown in Appendix 1.

4.3 Discussion of workability results

Analysis of the results on workability yielded the following conclusions :

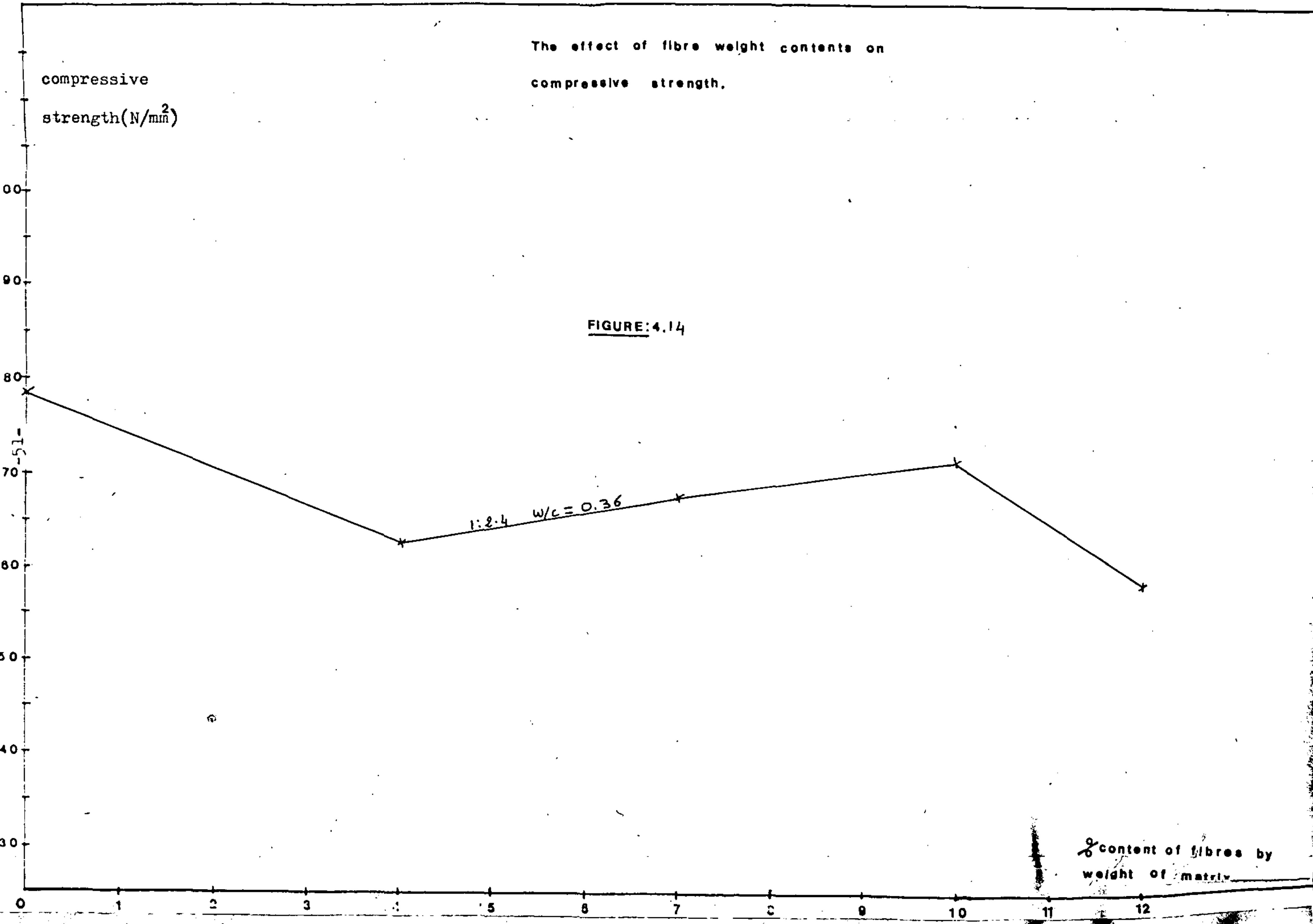
i) As it was expected, the melt extract steel fibres (grade 410, medium - coarse and 25mm long) were more workable than most of the existing drawn steel fibres. This fact is demonstrated by Figure 4.37 which contains Figure 4.2 reproduced from J. Edgington's[23] Ph.D. (page 38) of the mortar mix 1:2.4 with the V-B time - fibre percentage curve of my own mortar mix 1:2.4. From Figure 4.37 it seems that the equivalent aspect ratio of the melt extract fibres is around 55. Figure 4.37 shows that they are more workable than all the other fibres except the 53(B21N) fibres which are 0.38mm in diameter, 20mm long, brass coated and of an aspect ratio equal to 53. A simple calculation shows that the 25mm melt fibres have an equivalent diameter equal to 0.45mm which is small compared to the equivalent diameter calculated from the cross sectional area of the fibres. It can be concluded then that for a given length and cross sectional area a fibre with a dished cross section is more workable than a fibre with a circular cross section;

ii) The slump decreases and the V-B time increases with fibre content



The effect of fibre weight contents on compressive strength.

FIGURE:4.13



The effect of fibre weight contents on compressive strength.

FIGURE:4.14

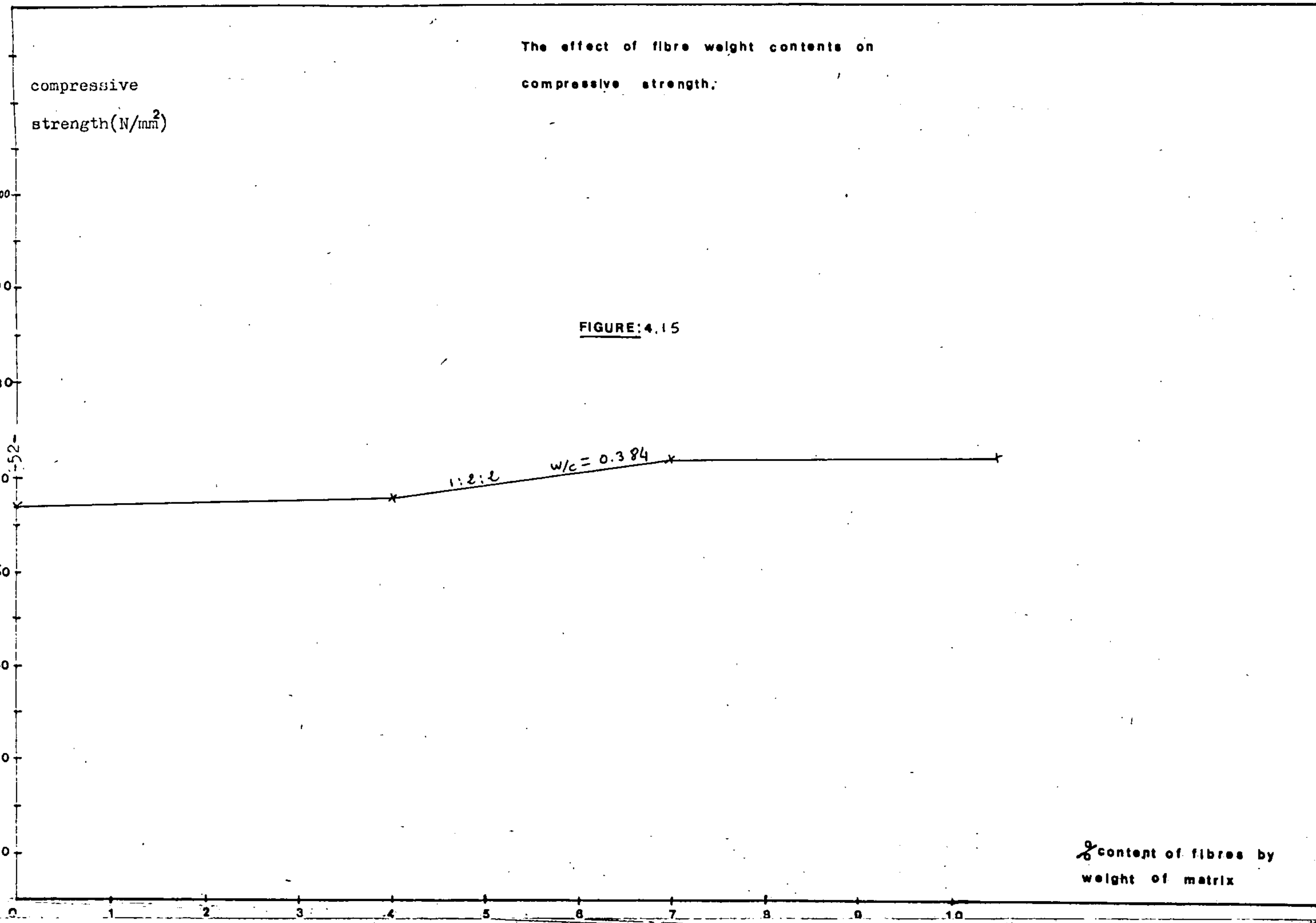
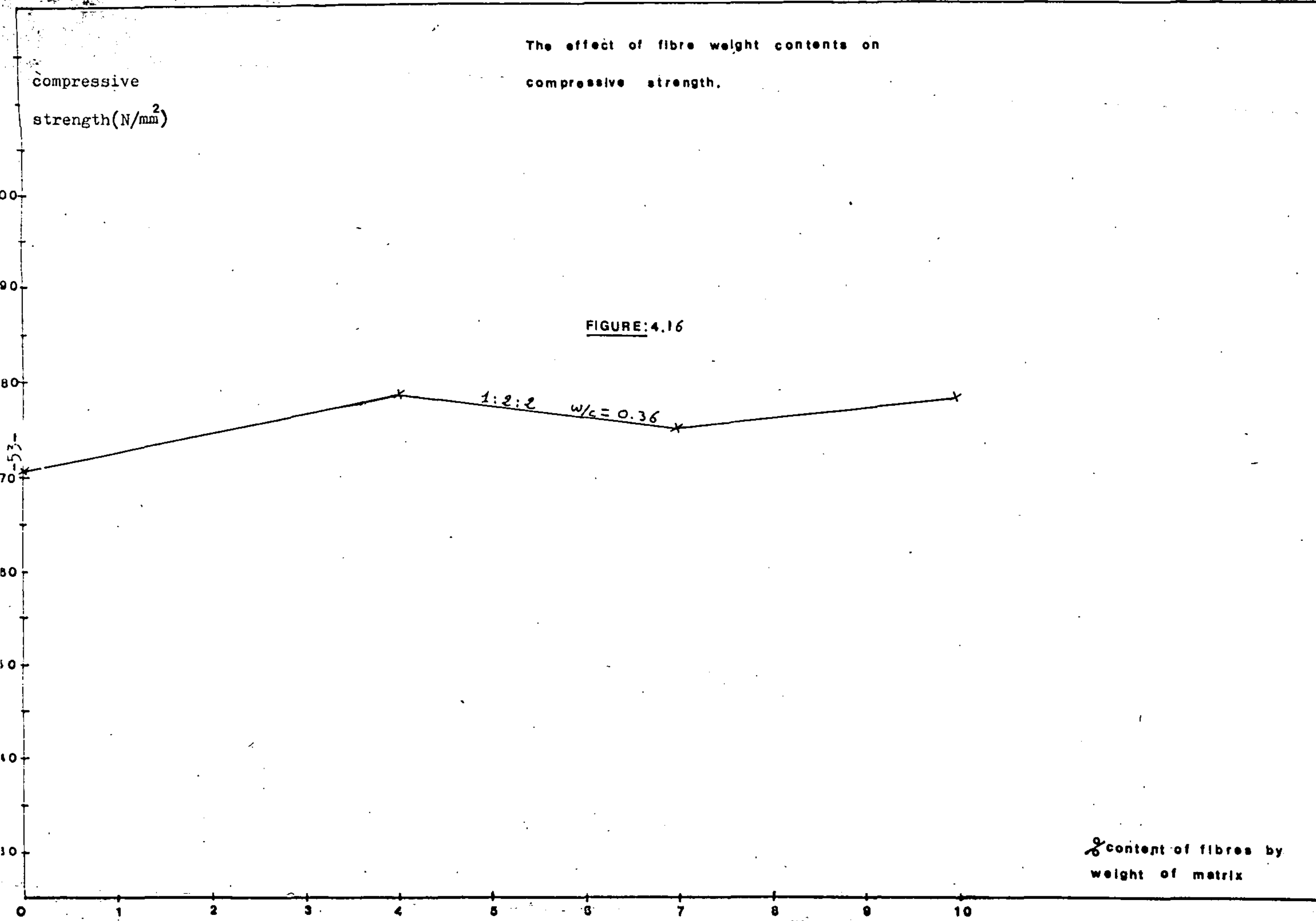


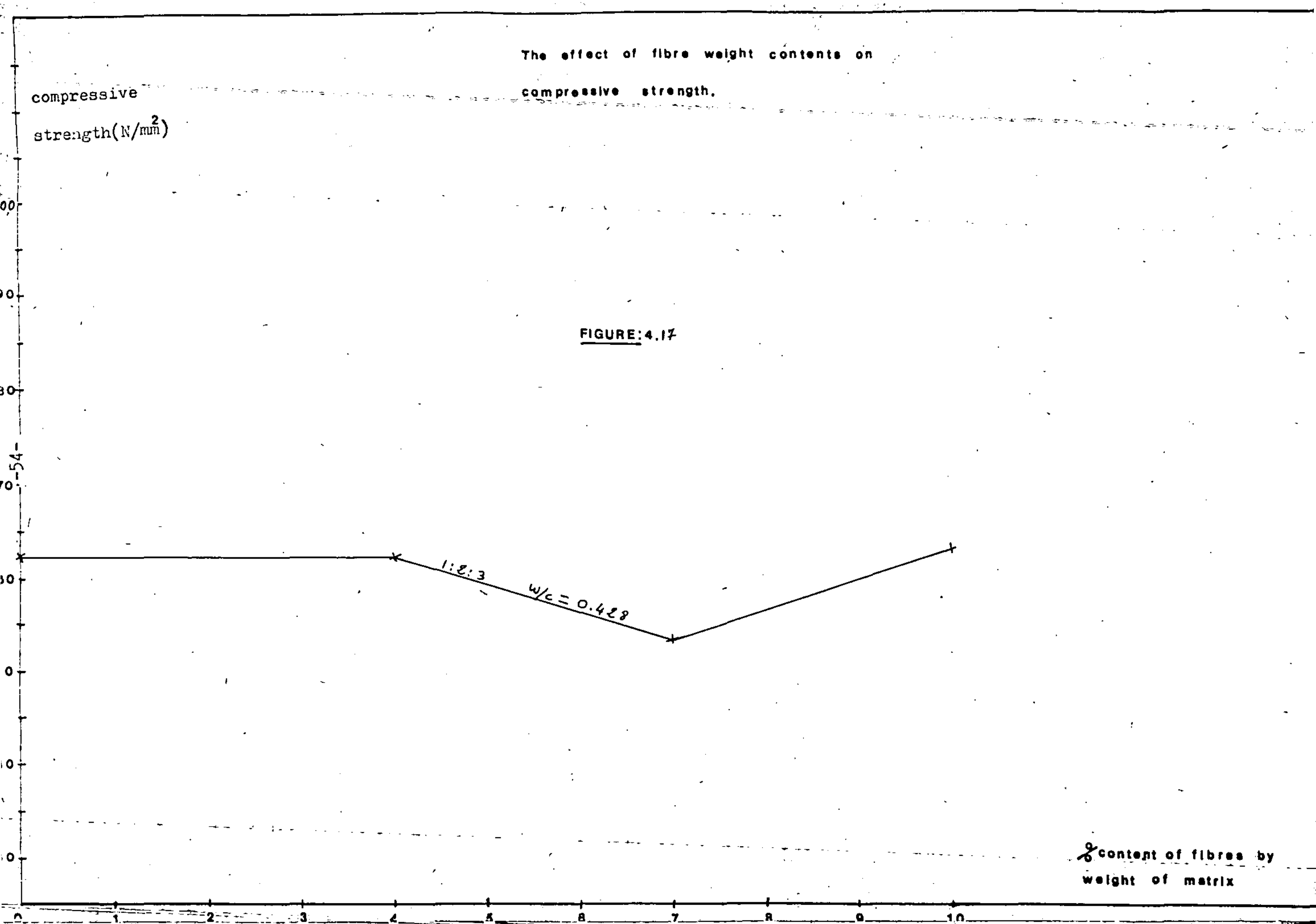
FIGURE:4.15

The effect of fibre weight contents on compressive strength.



The effect of fibre weight contents on compressive strength.

FIGURE:4.16



The effect of fibre weight contents on compressive strength.

FIGURE:4.17

The effect of fibre-weight contents on compressive strength.

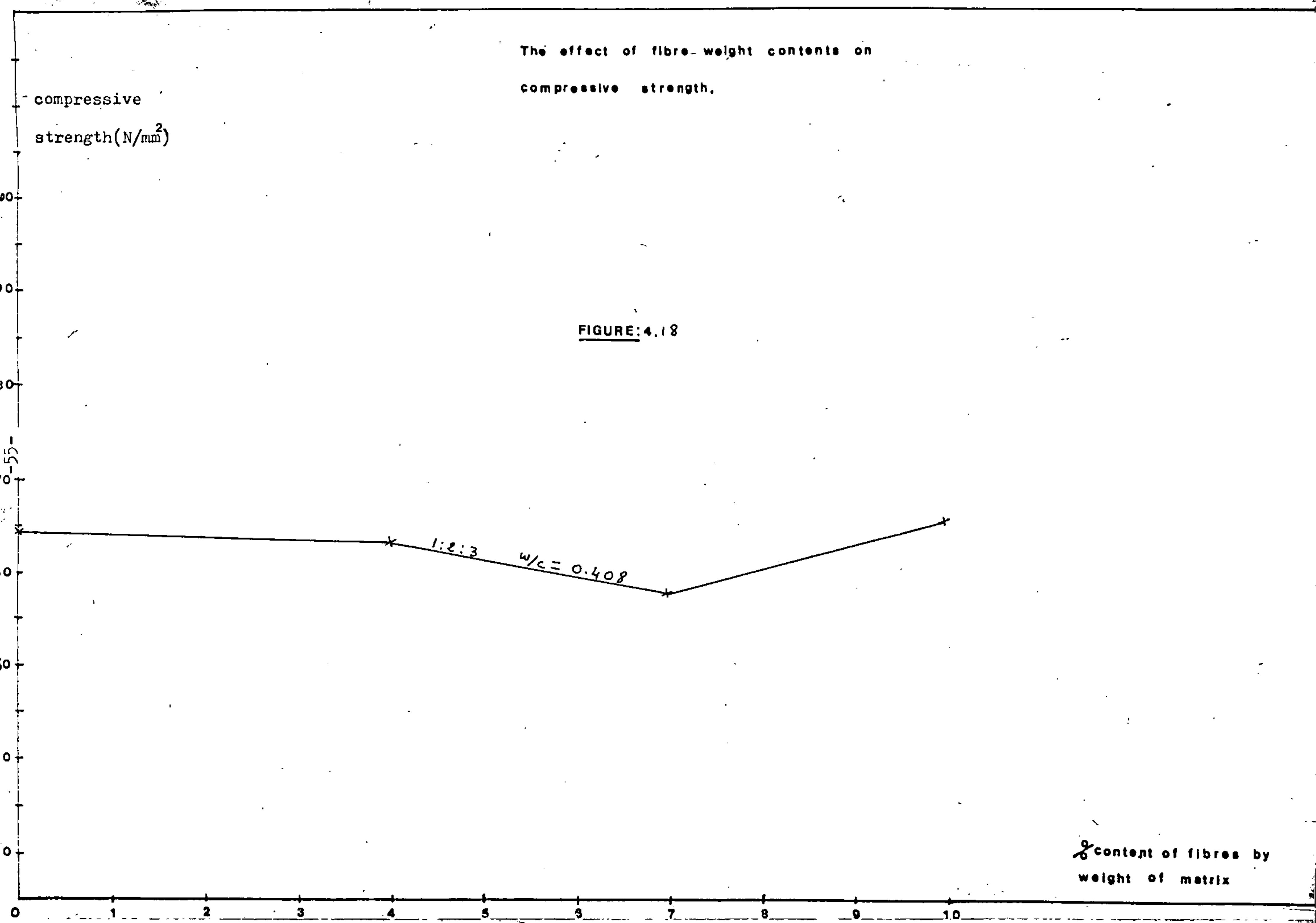
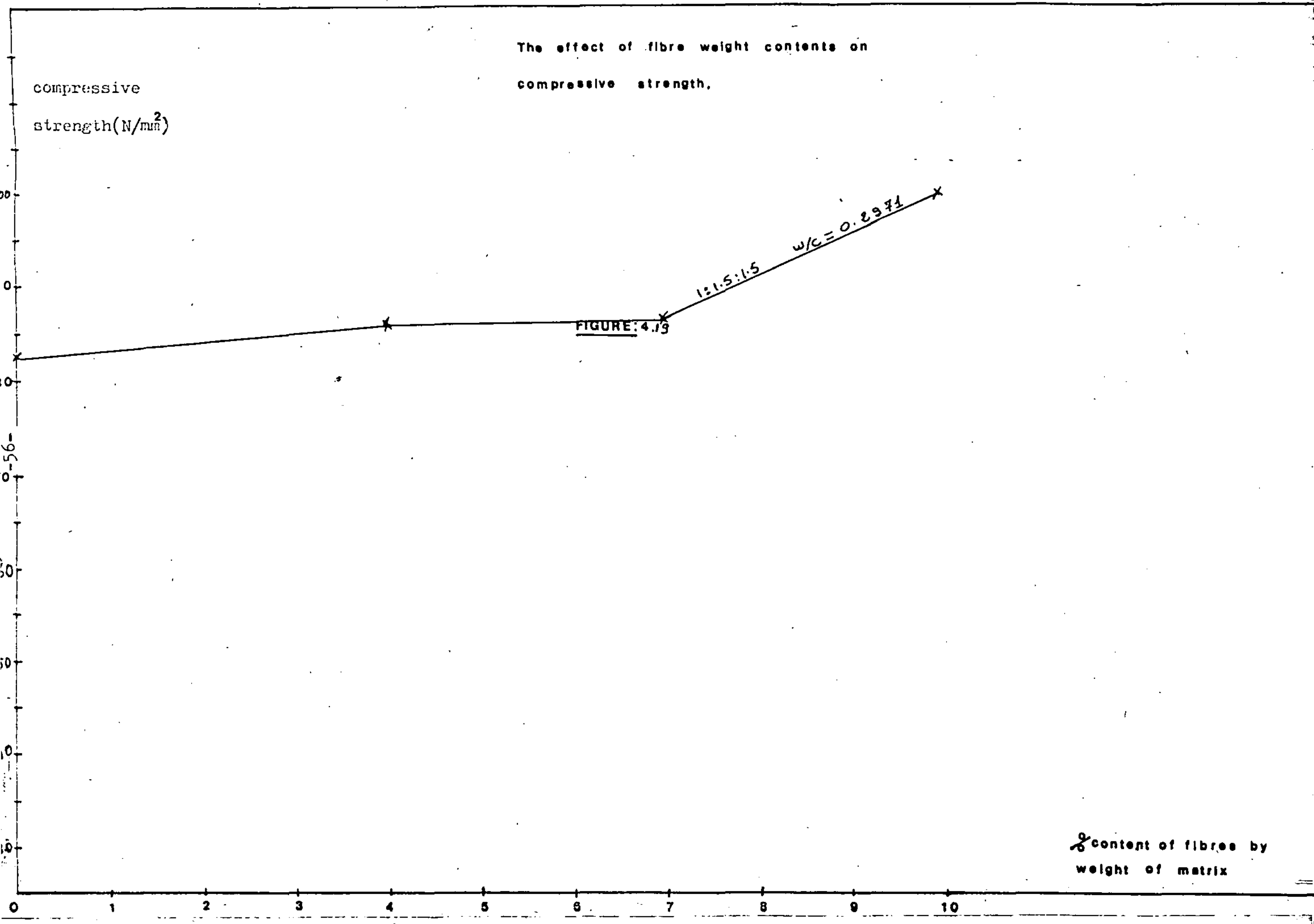


FIGURE:4.18



The effect of fibre weight contents on compressive strength,

FIGURE: 4.13

The effect of fibre weight contents on compressive strength.

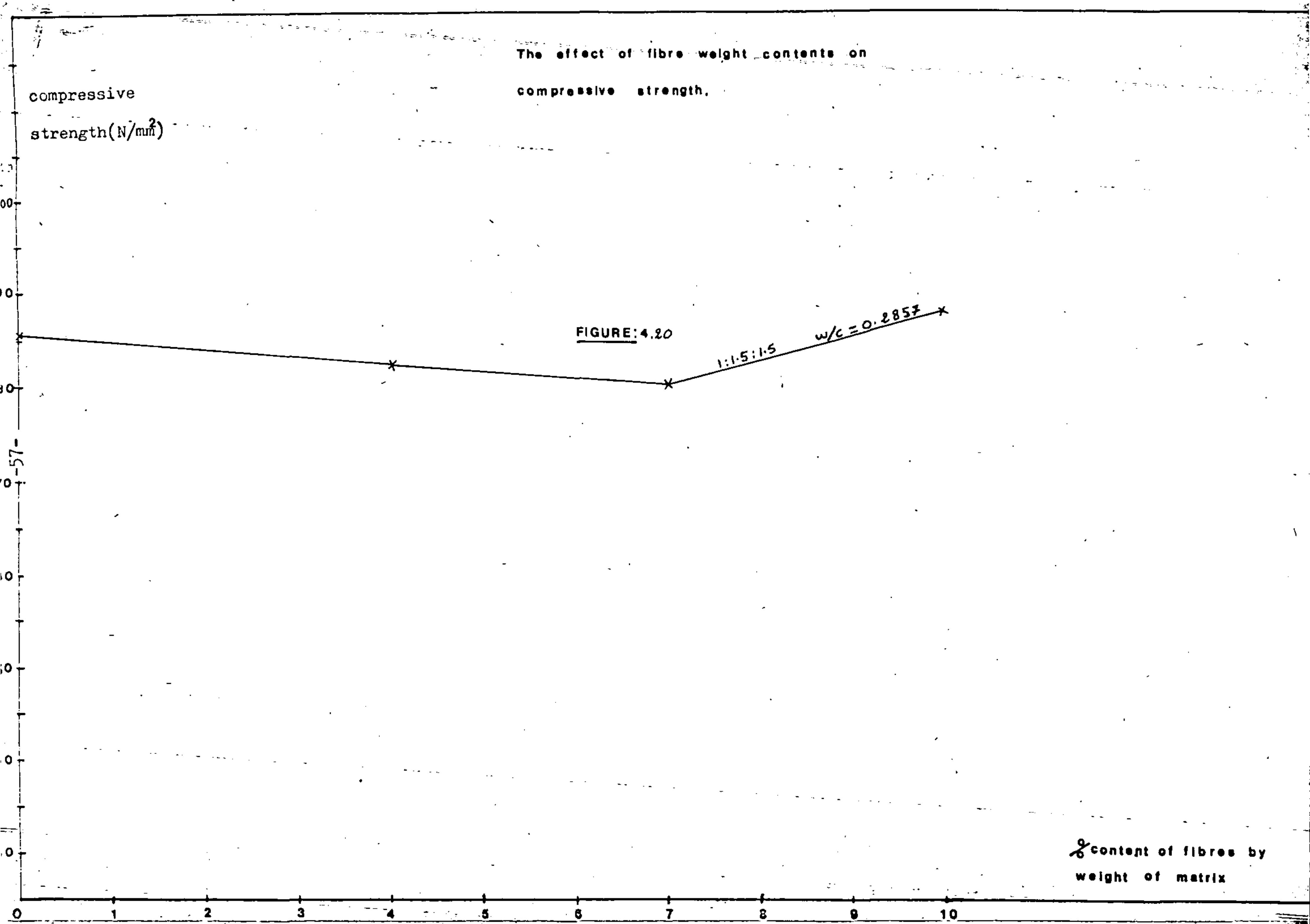
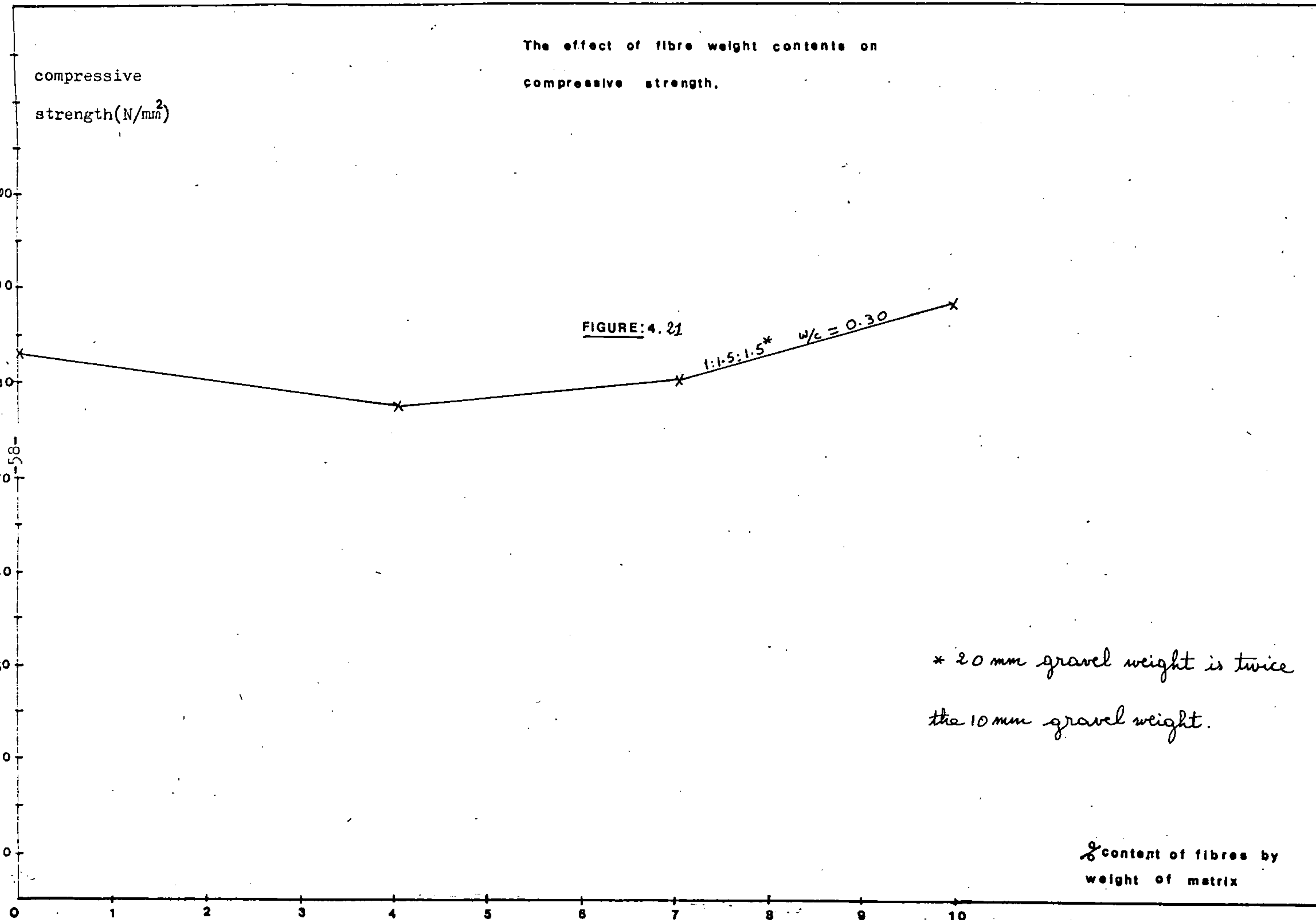
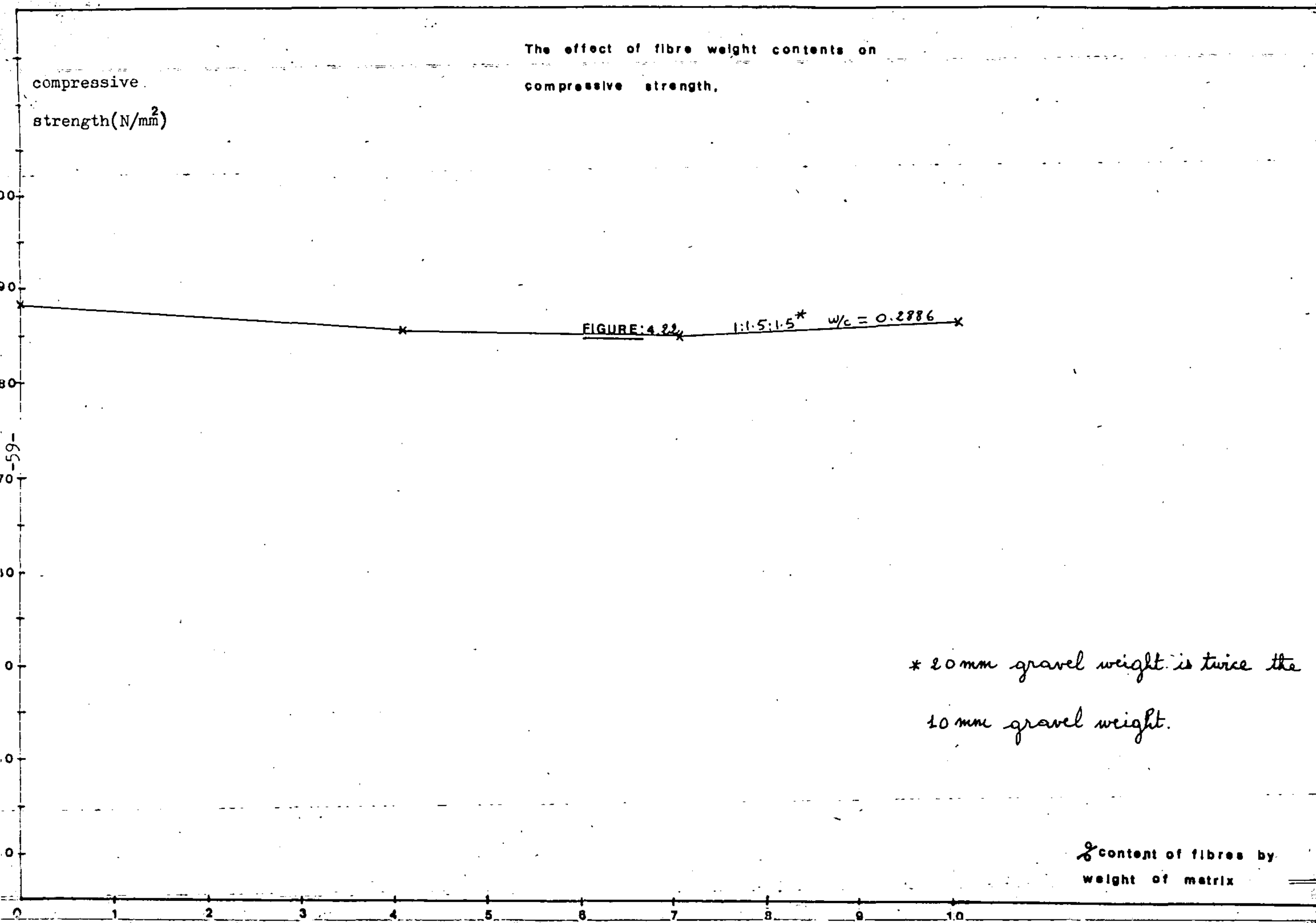


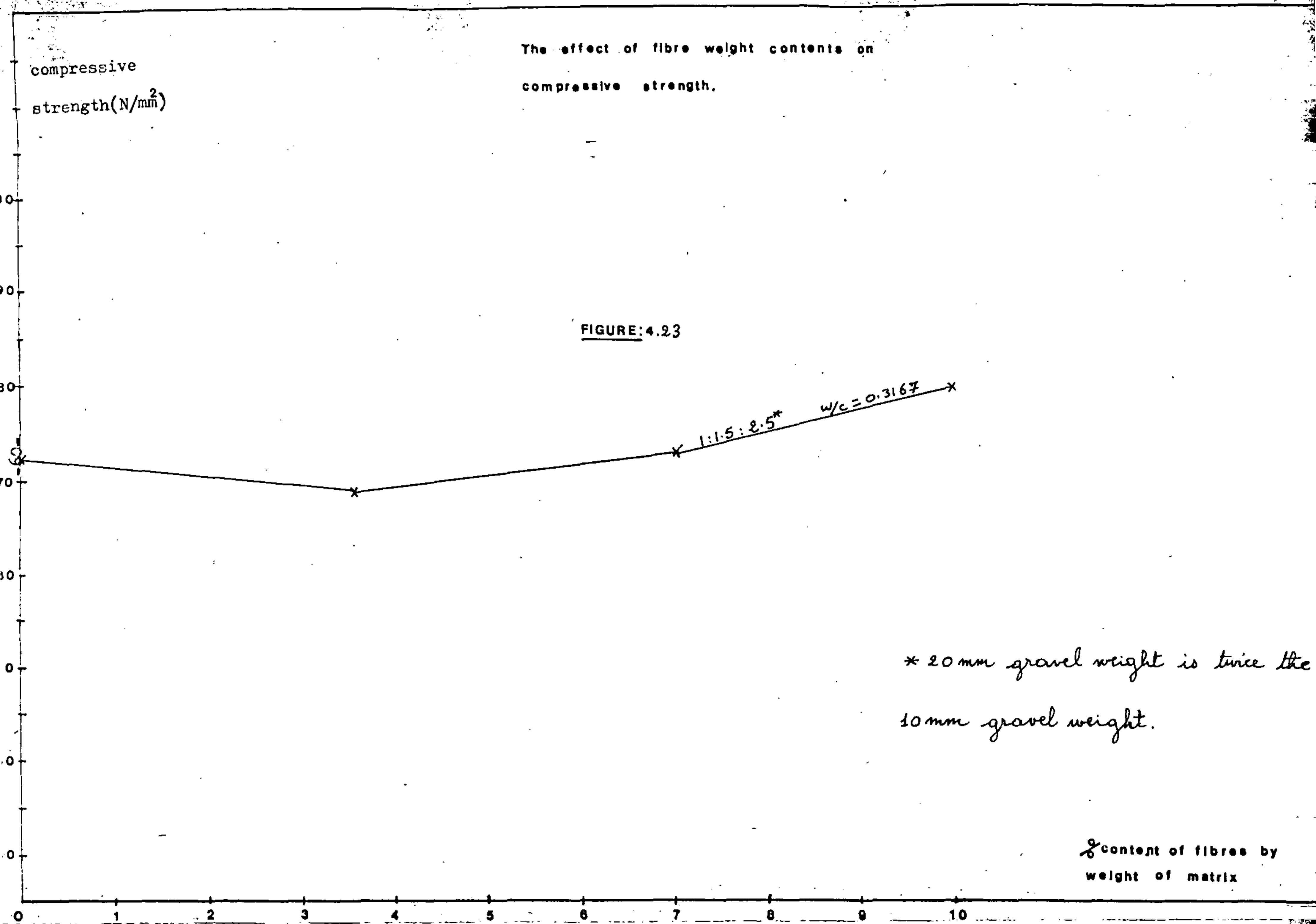
FIGURE: 4.20



The effect of fibre weight contents on compressive strength.

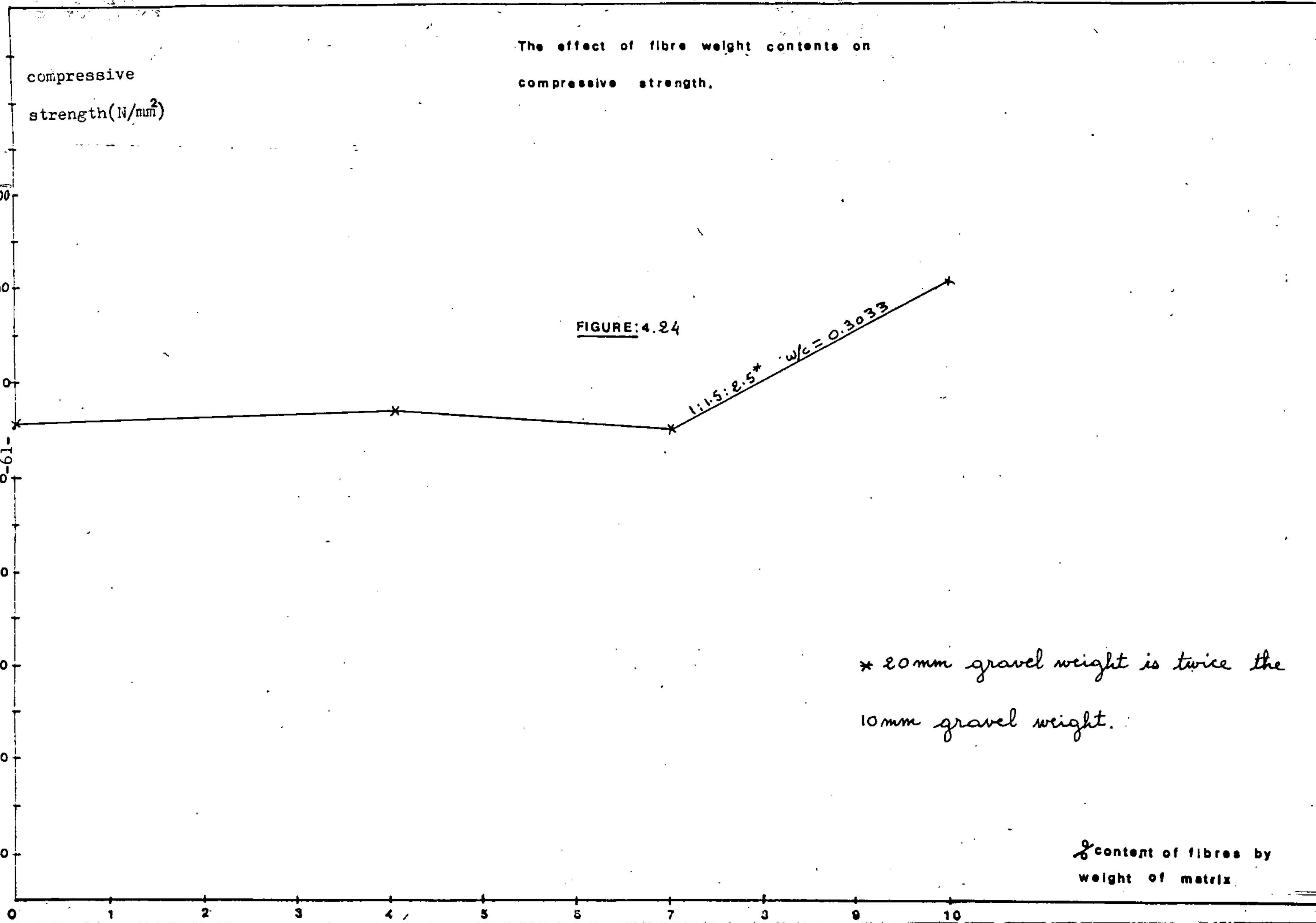
FIGURE: 4.21


The effect of fibre weight contents on compressive strength,
compressive strength(N/mm²)
90
80
70
FIGURE:4.22
1:1.5:1.5* w/c = 0.2886
* 20mm gravel weight is twice the 10mm gravel weight.
% content of fibres by weight of matrix
0
1
2
3
4
5
6
7
8
9
10

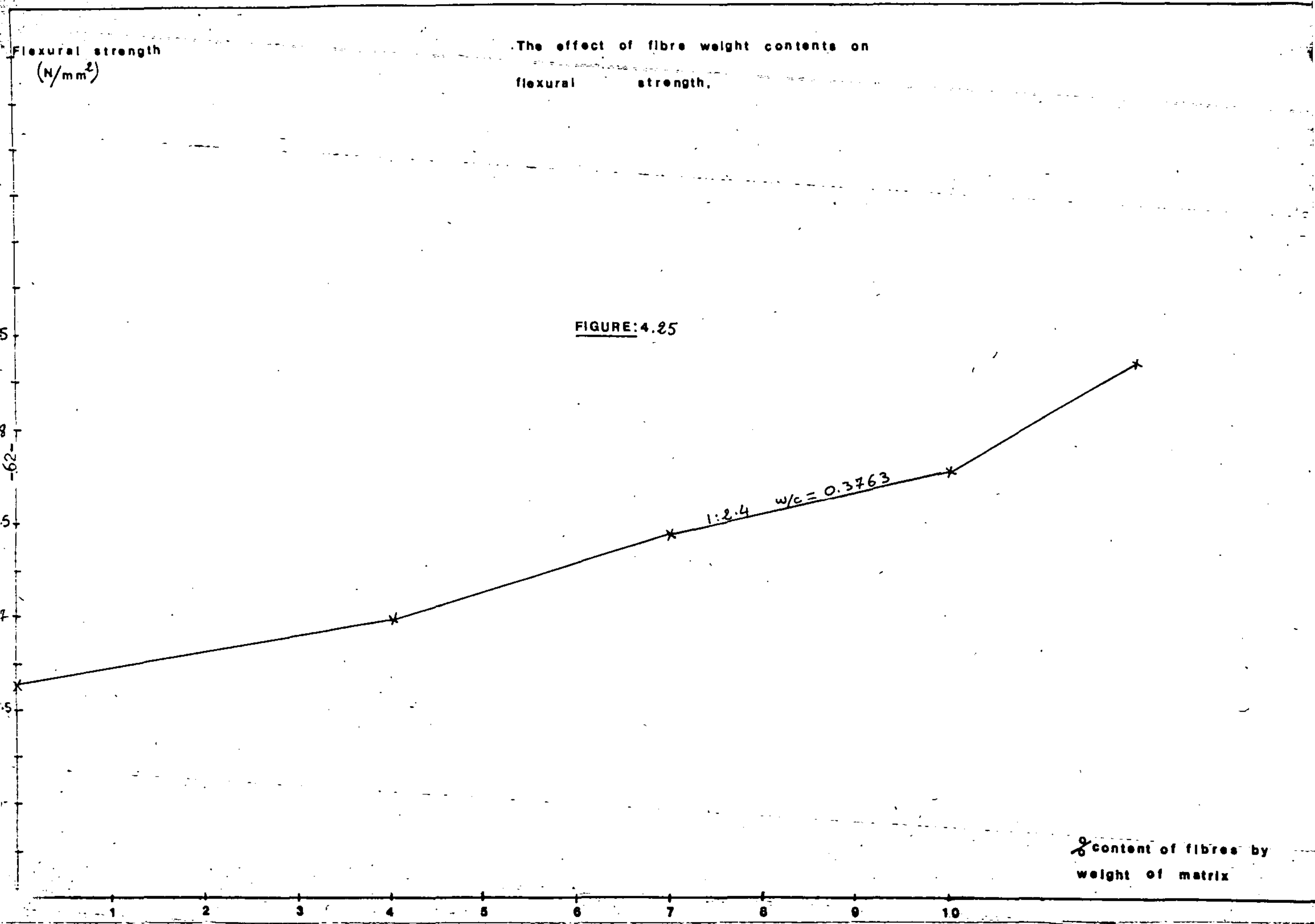


The effect of fibre weight contents on compressive strength.

FIGURE: 4.23

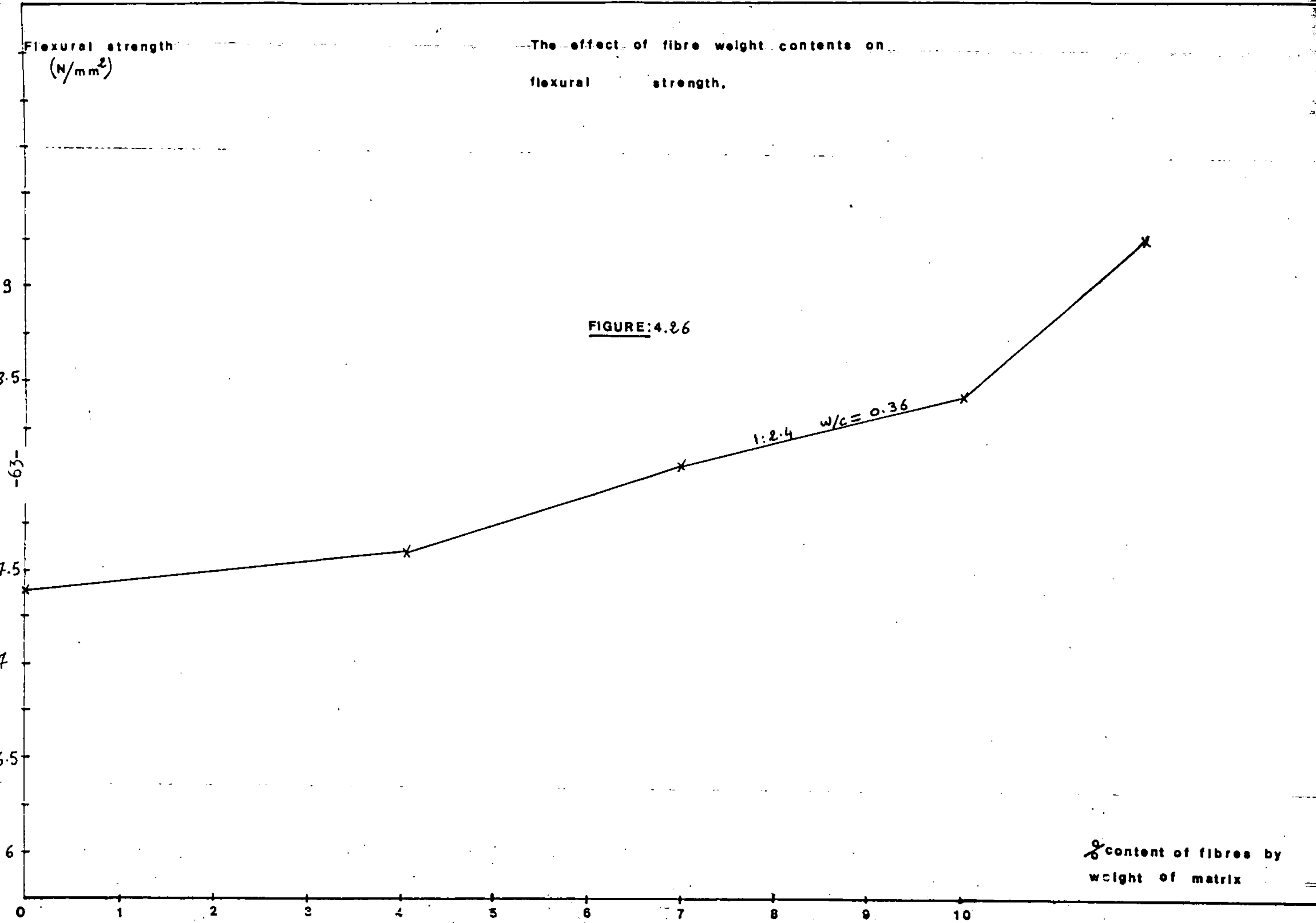


The effect of fibre weight contents on compressive strength.
compressive strength(N/mm^2)
FIGURE:4.24
1:1.5:2.5* w/c = 0.3033
* 20mm gravel weight is twice the 10mm gravel weight.
% content of fibres by weight of matrix
0
1
2
3
4
5
6
7
8
9
10



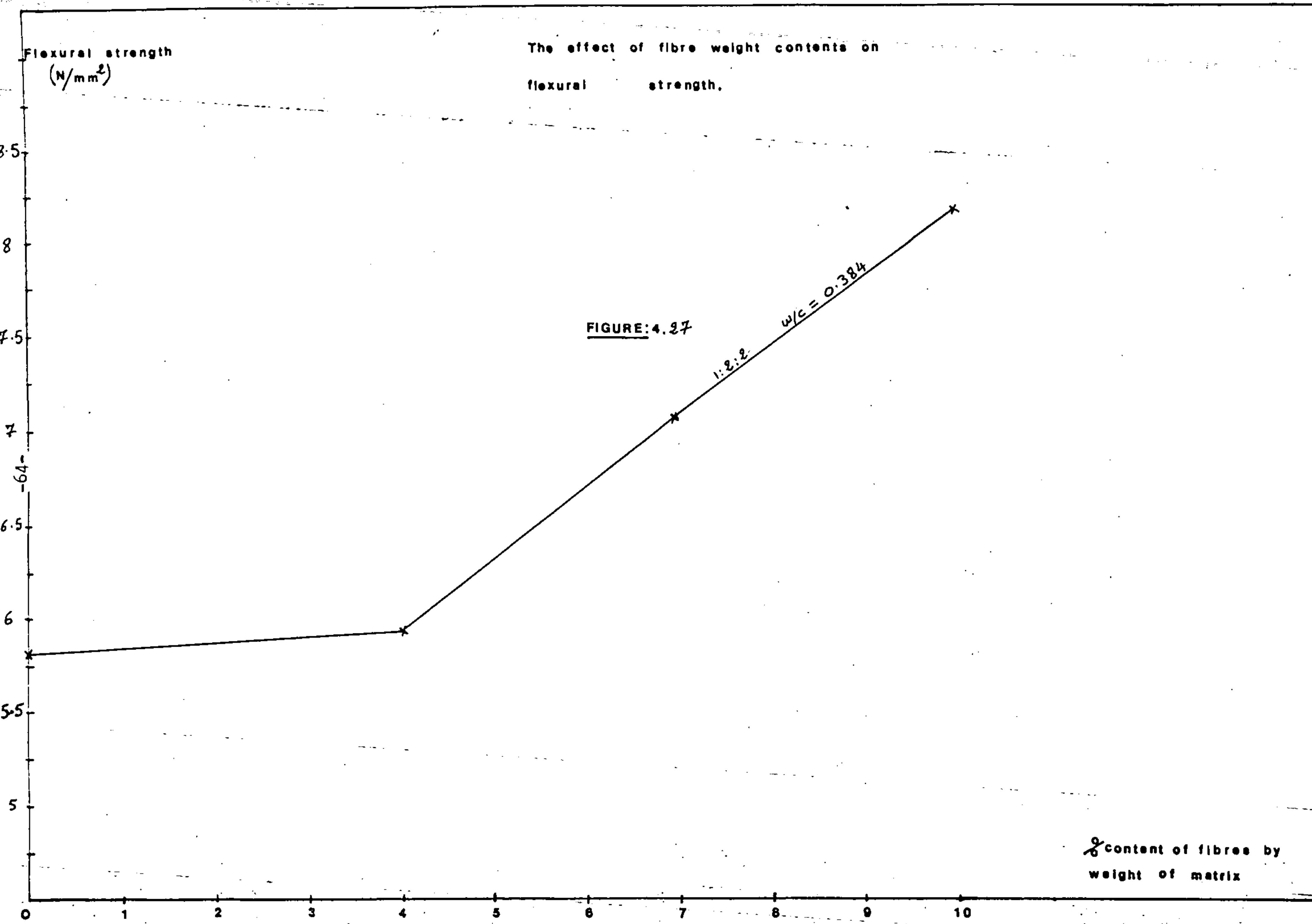
The effect of fibre weight contents on flexural strength.
Flexural strength (N/mm²)
1:2.4 w/c = 0.3763
% content of fibres by weight of matrix
1
2
3
4
5
6
7
8
9
10

FIGURE: 4.25



The effect of fibre weight contents on flexural strength.

FIGURE: 4.26


Flexural strength (N/mm²)
The effect of fibre weight contents on flexural strength.
FIGURE: 4.27
1:2:2
w/c = 0.384
% content of fibres by weight of matrix
8.5
8
7.5
7
6.5
6
5.5
5
0
1
2
3
4
5
6
7
8
9
10

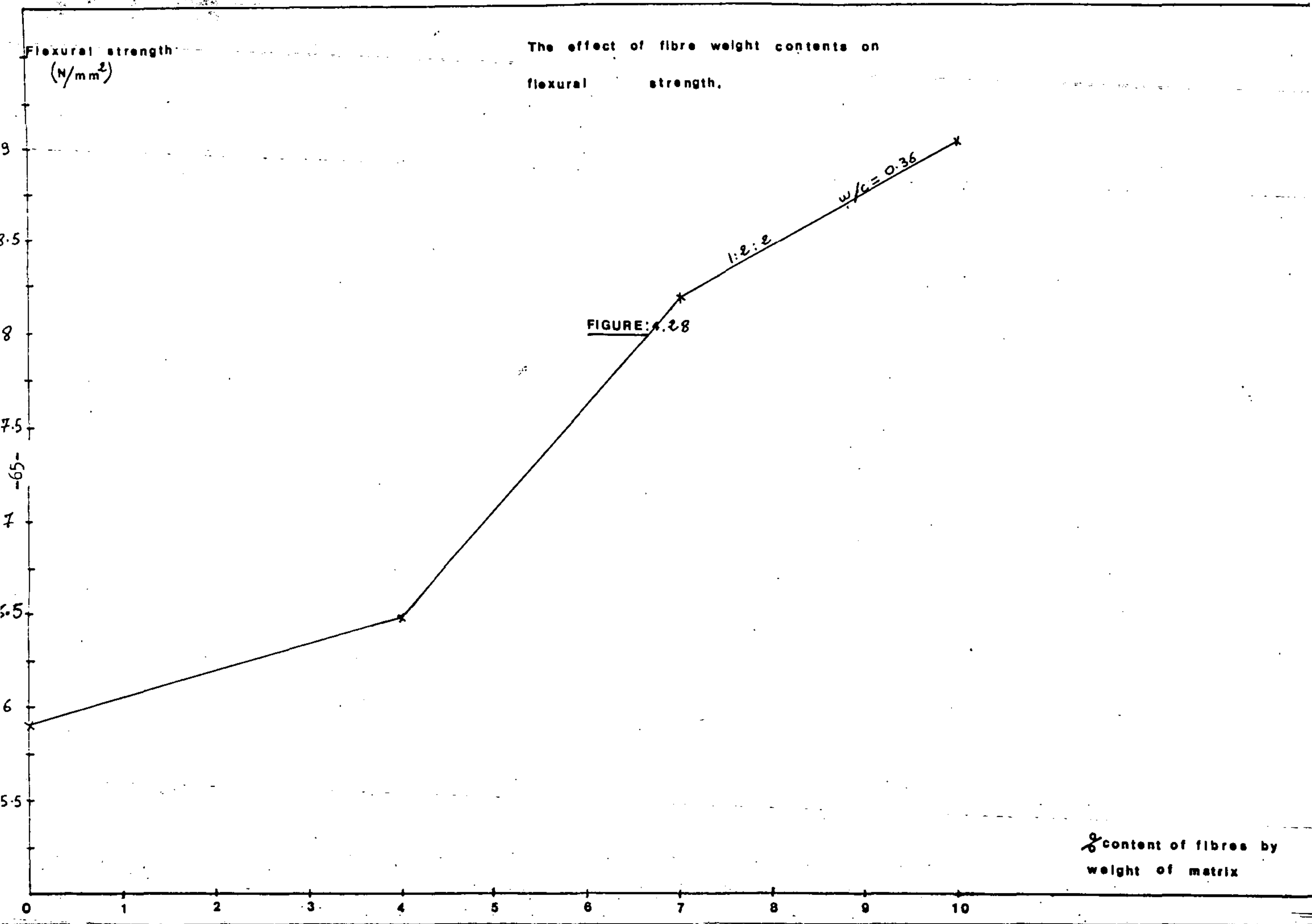
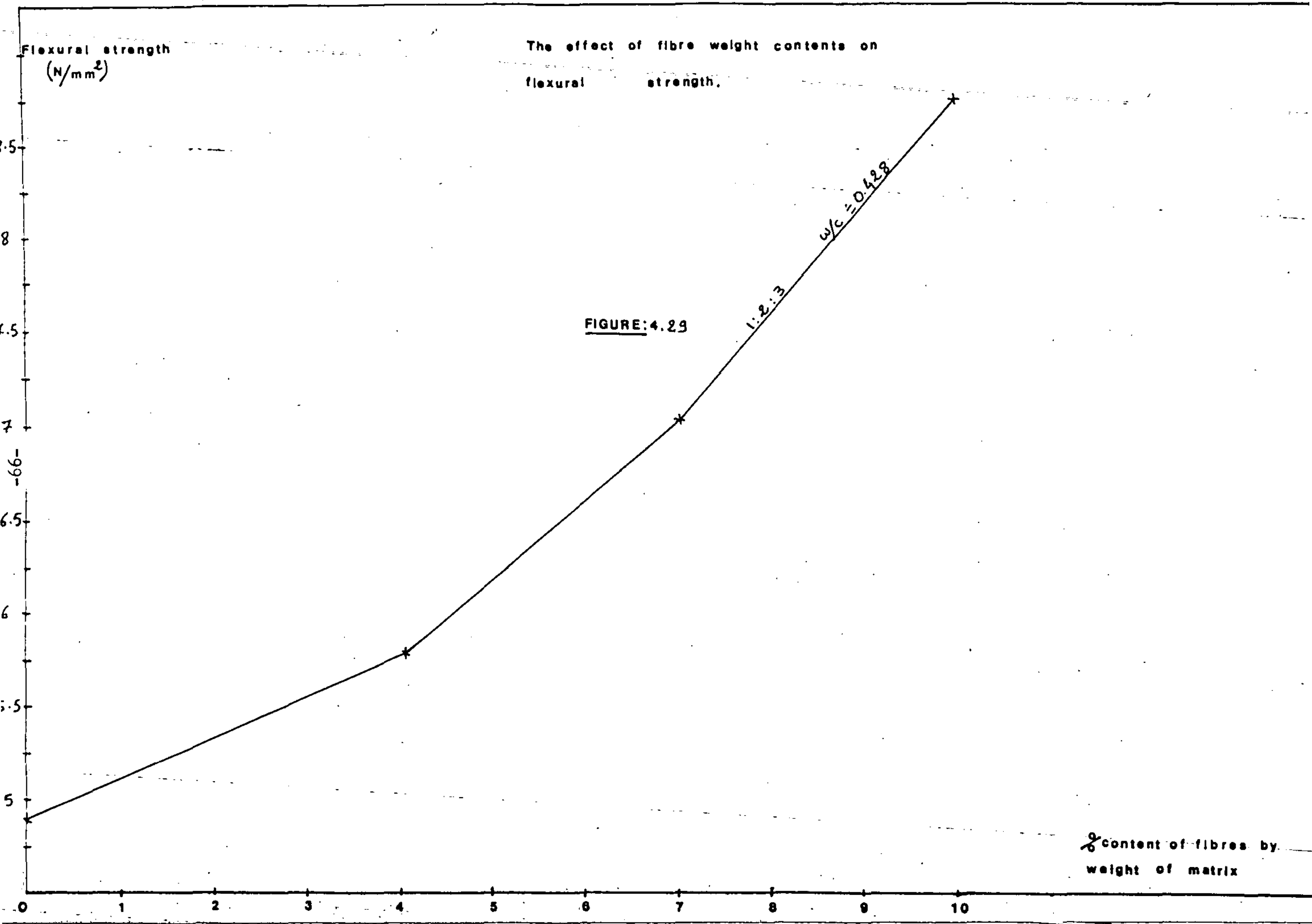


FIGURE: 4.28

The effect of fibre weight contents on flexural strength.



The effect of fibre weight contents on flexural strength.

FIGURE:4.29

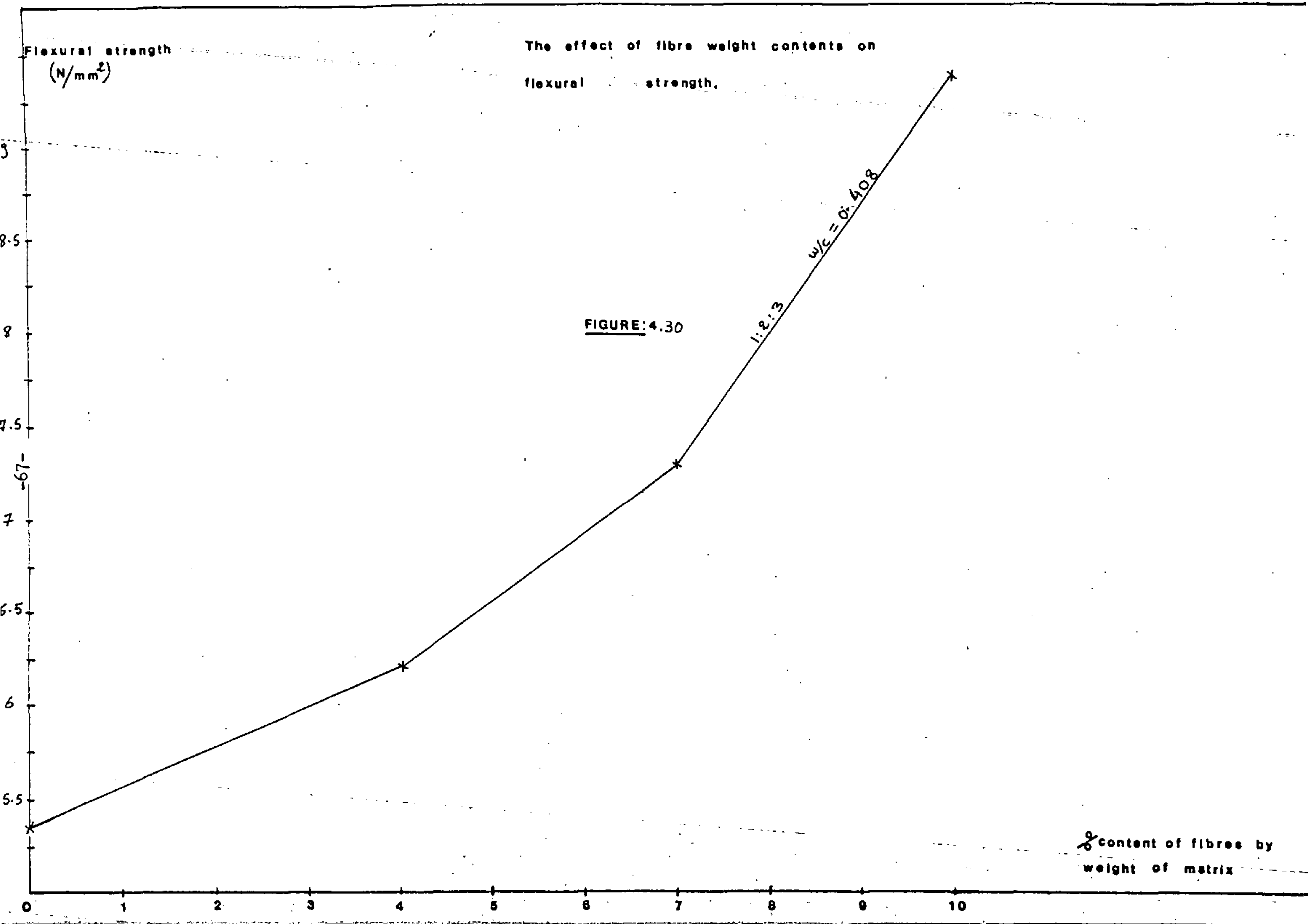
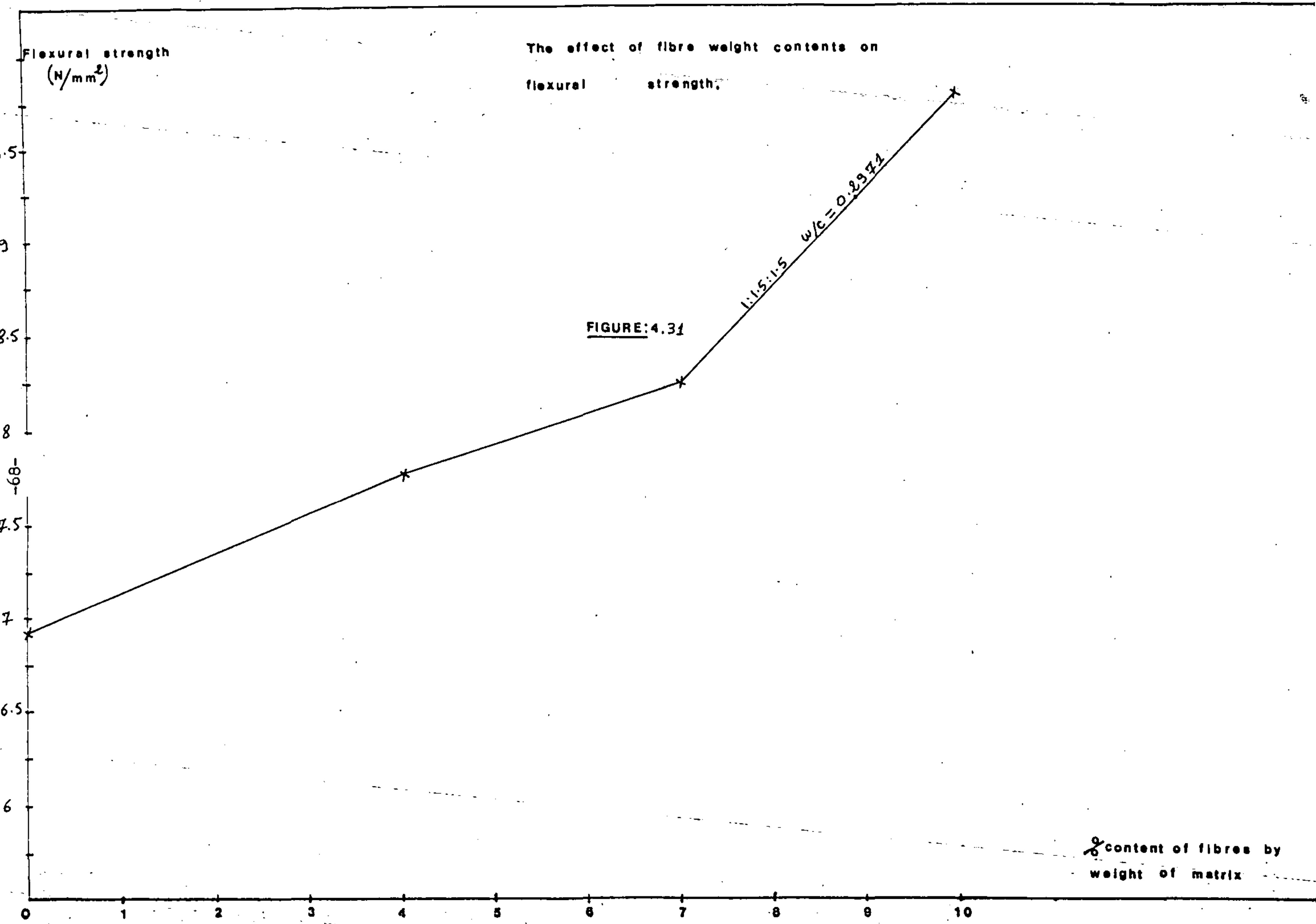


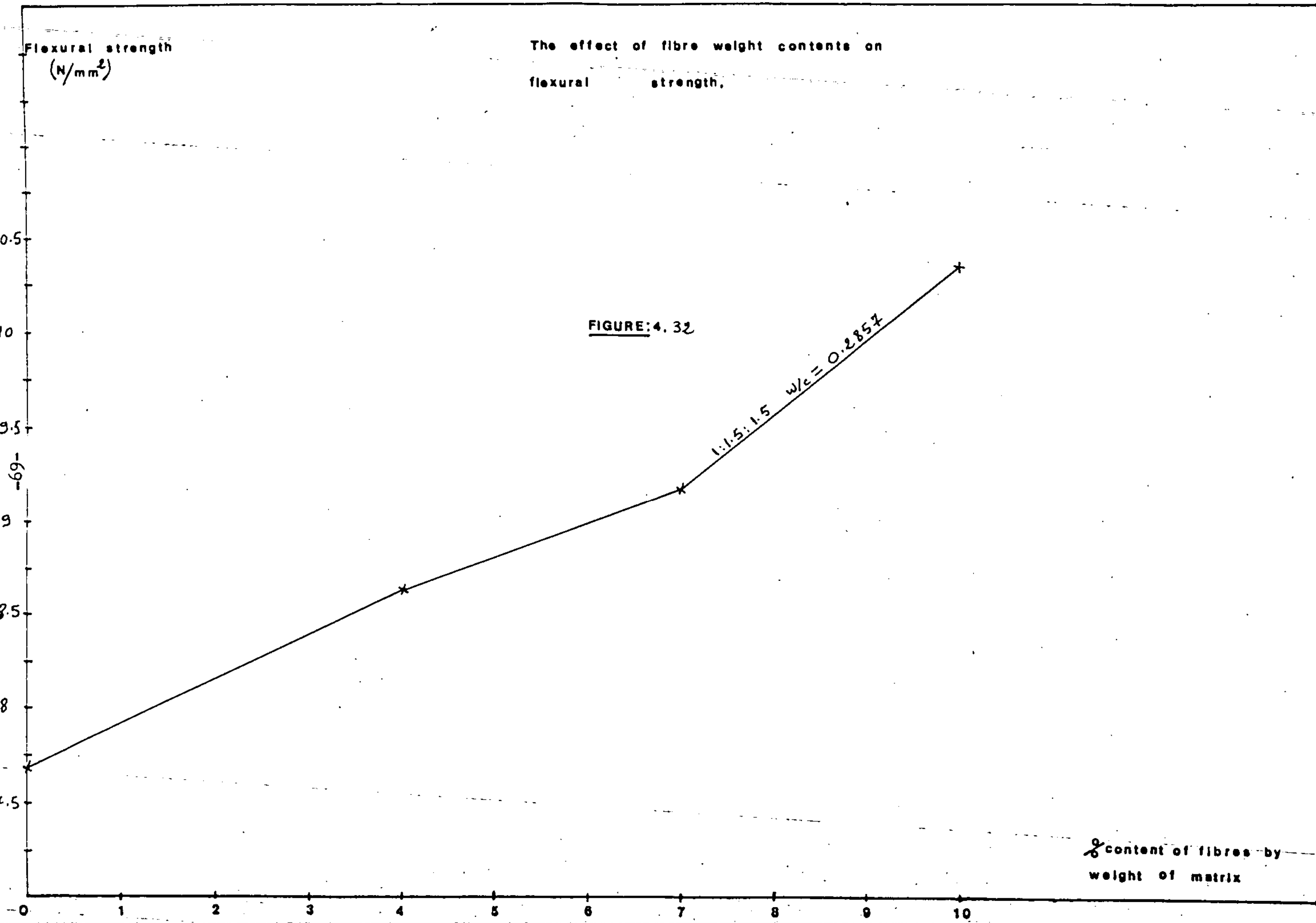
FIGURE: 4.30

The effect of fibre weight contents on flexural strength.



The effect of fibre weight contents on flexural strength.

FIGURE: 4.31



The effect of fibre weight contents on flexural strength.

FIGURE: 4.32

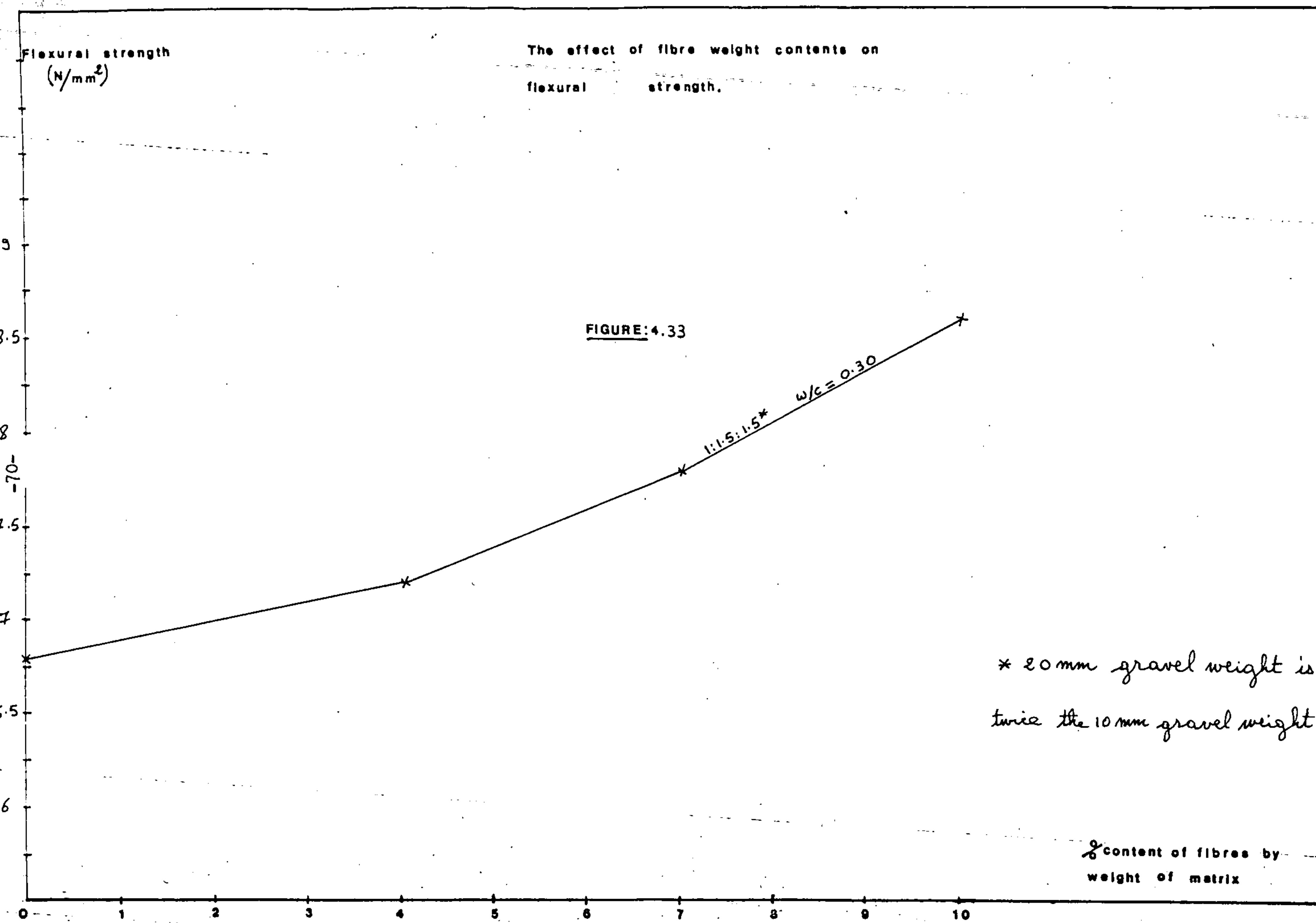


FIGURE: 4.33 The effect of fibre weight contents on flexural strength.

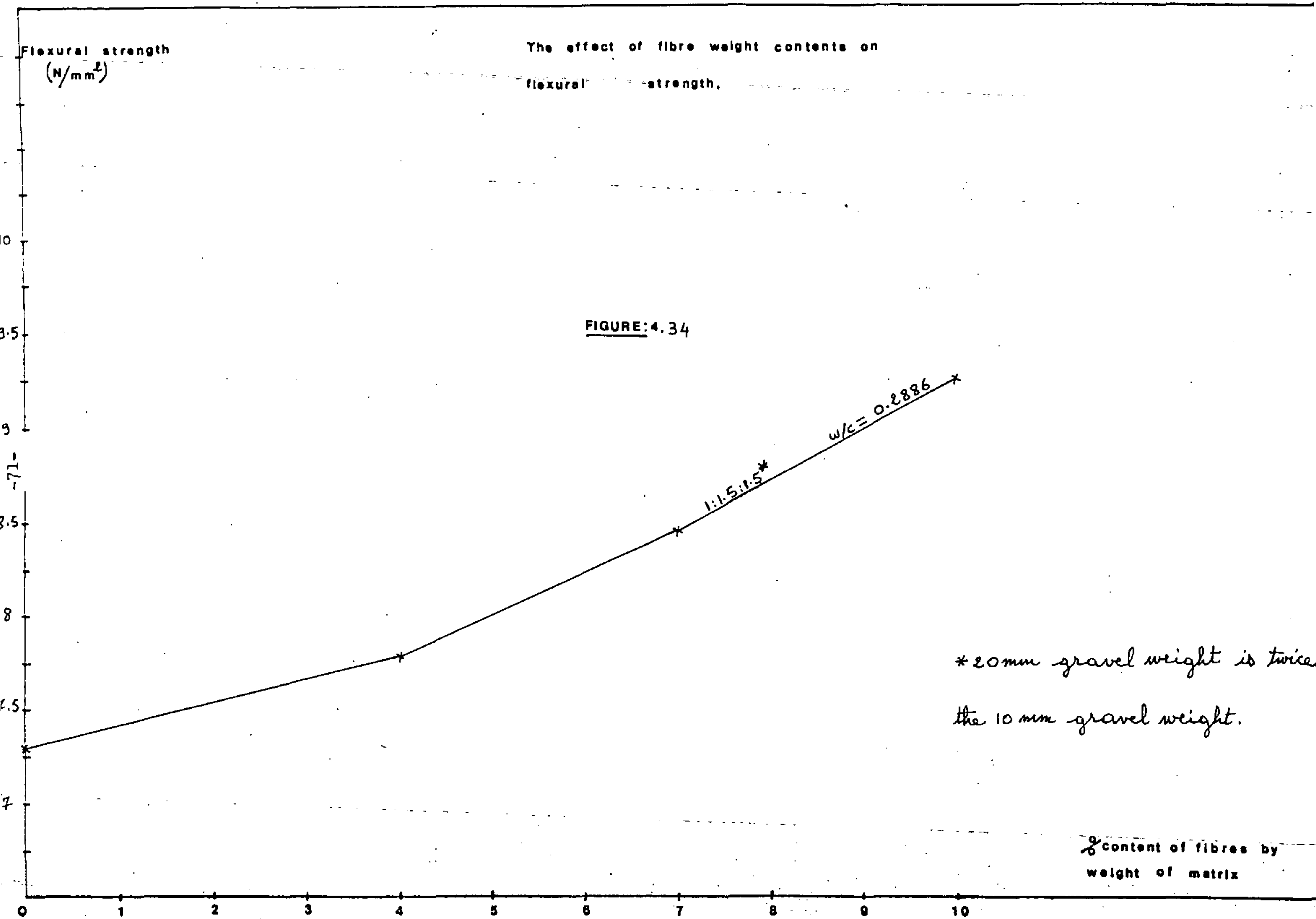


FIGURE: 4.34

The effect of fibre weight contents on flexural strength.

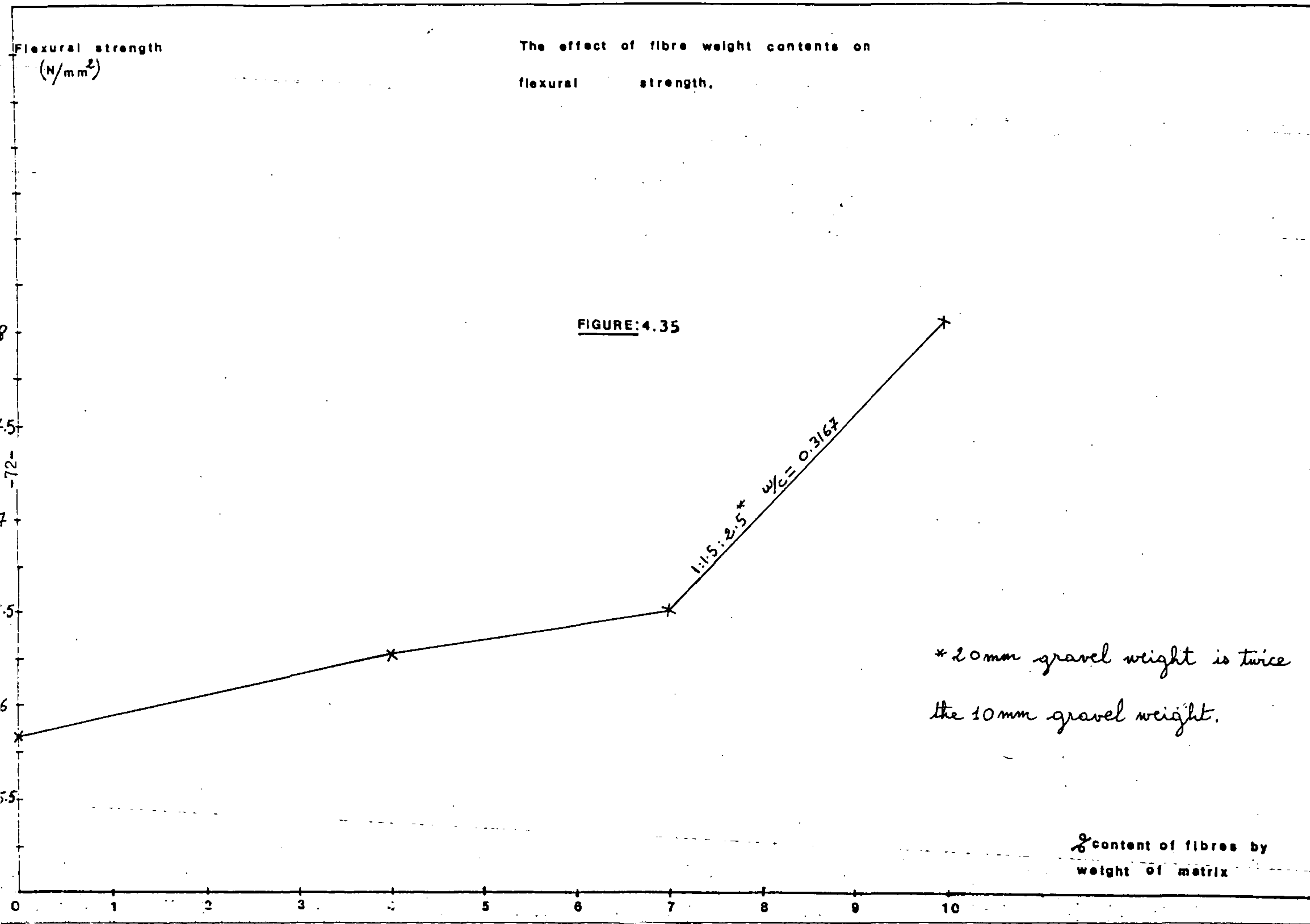
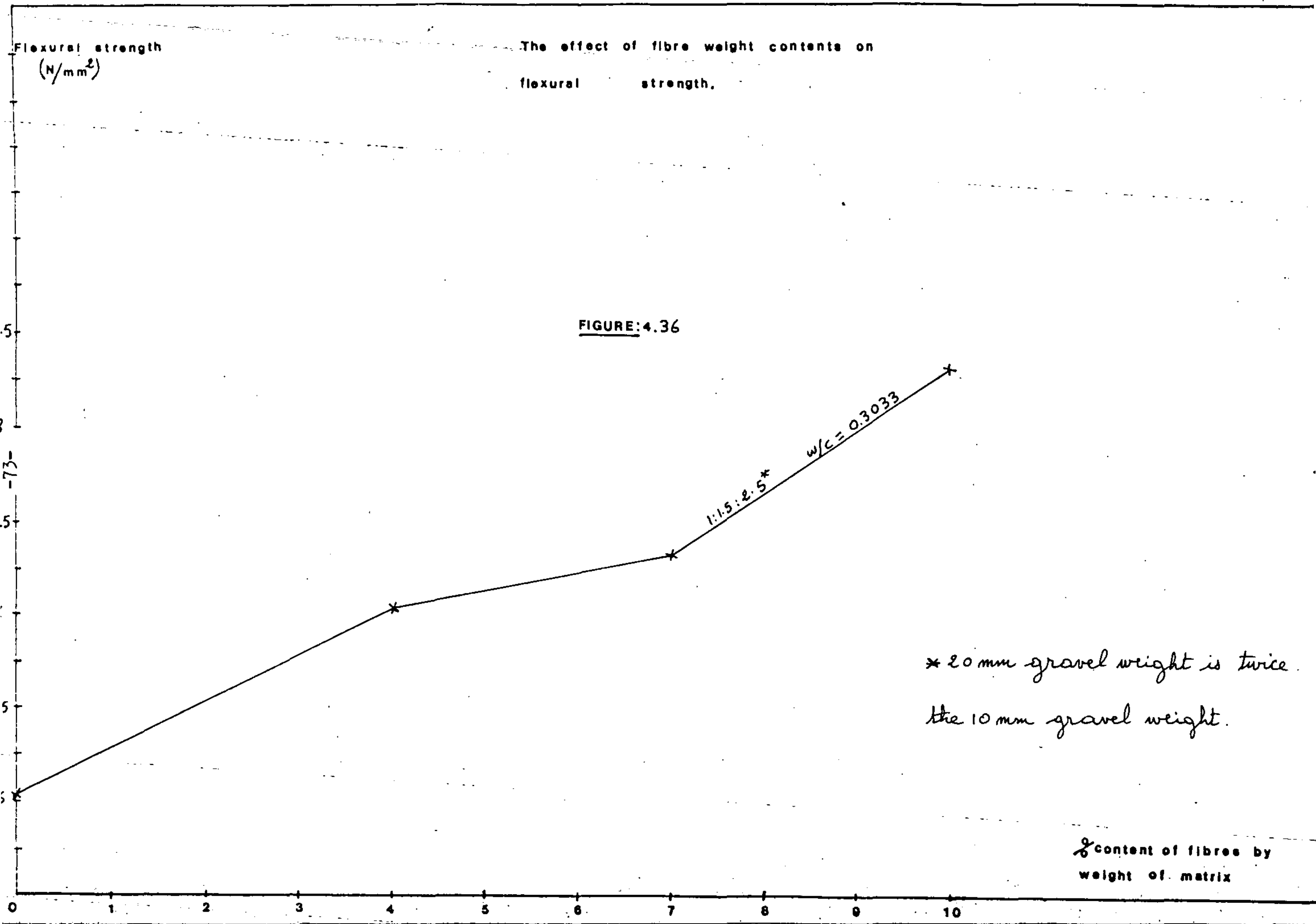


FIGURE:4.35 The effect of fibre weight contents on flexural strength.



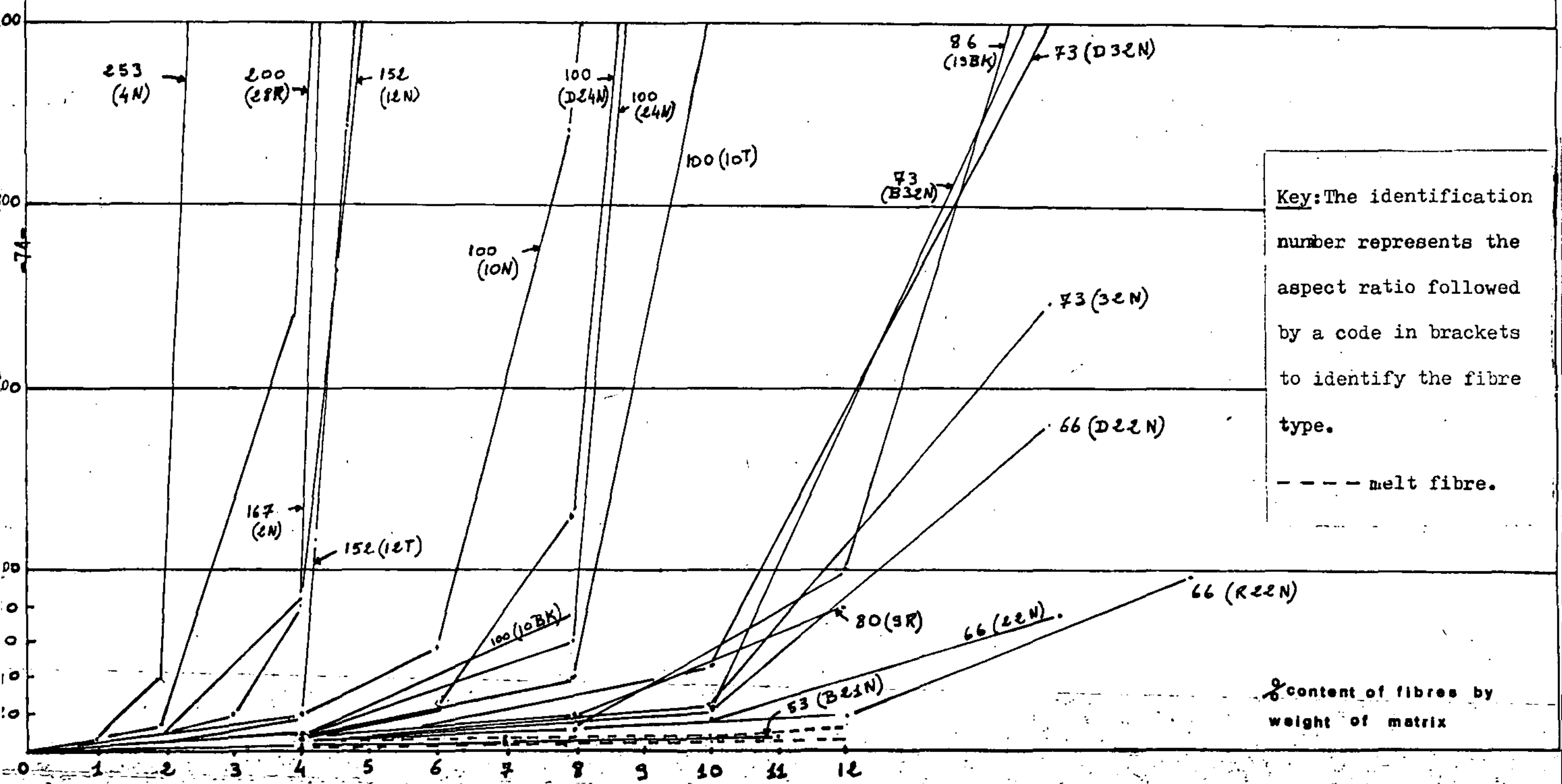
The effect of fibre weight contents on flexural strength.

FIGURE:4.36

The effect of fibre aspect ratios on V-B time

FIGURE: 4.37

After J.D. Edgington



in every matrix investigated. In the case of the V-B time the increase has the shape of an exponential function;

iii) In the mortar mix the slump and the V-B time progressively decreases and increases respectively, whereas this behaviour is more pronounced in the concrete matrices. The slump decreases and the V-B time increases when the matrix changes from mortar to 20mm aggregate concretes;

iv) The admixture conplast 337 was effective in reducing the water/ cement ratios without loss of workability.

v) There was no unique relationship between fibre content and the slump or V-B time;

vi) Despite the consideration of the V-B time as the most realistic assessment of workability for fibre reinforced composites, the slump test proved with this fibre composites to be sensitive when used, therefore it is recommended to be carried out as an easy test on site.

4.4 Discussion of the flexural test results

The bond strength between the fibres and the matrix and the orientation of the fibres in the matrix must be understood before anticipating how steel fibres are likely to affect the properties of mortar or concrete.

i) The application of load causes transfer of stress from the matrix to the fibres by interfacial shear. This transfer of stress takes place before and after cracking of the matrix. Before cracking they impart additional strength and after the cracking has started they modify the inherently brittle behaviour of the matrix. The melt extract fibres developed intimate bonds with the matrix. It was noticed that some of them broke and some of them pulled out after the beams broke;

ii) The arrangement of the fibres in the matrix has an important influenee on their strengthening. Fibres orientated parallel to the direction of the applied stress have maximum effect. It was noticed during the experiment that under table vibration there was a tendency for the steel fibres to be aligned in planes at right angles to the direction of vibration or gravity. This was beneficial in order to increase the flexural strength.

A study of the flexural test results led to the following observations :

i) The composite strength increases as the fibre content increases;

ii) The increase in the modulus of rupture of the mortar mix, provided by the addition of 12% fibre by weight of the matrix, was around 26%. The addition of 10% fibre by weight of the matrix gives an increase between 40 and 50 per cent for mix B and an increase between 70 and 80 per cent for mix C. When 10% fibre by weight of the matrix is added to matrix D, the increase varies between 30 and 40 per cent, whereas it is around 27% for matrix E and around 38% for matrix F. It is obvious that the higher the ratio of aggregate to cement, the higher is the increase in the modulus of rupture. The presence of 10mm aggregate tend to give a better increase than the 20mm aggregate (see Table 4.1).

4.5 Discussion of the compressive test results

The inclusion of melt extract steel fibre in the mixes gave either an insignificant increase and sometimes even a decrease in compressive strength. It was realised that as for every inclusion of other steel fibres, the compressive strength is affected very little.

4.6 Examples of how to use the results to relate workability, percentage of fibres and flexural strength in the different mixes

Before giving examples of how to use the previous results, Figure 4.38 shows the relation between the slump loss and flexural strength gain. The loss in slump was determined by subtracting the slump of the mix from the slump at 0% fibre content. The gain in flexural strength was obtained by subtracting the strength of the composite from the strength of the composite without fibre. These values were plotted on the figure and the best fitting curves for the points drawn. Each curve is identified by a letter and a number between brackets, the letter being the mix name and the number being the slump in mm at 0% fibre. The nearest point of each curve to the origin of the axes corresponds to 4% by weight of fibre and the second nearest to the origin of the axes corresponds to 7% by weight of fibre and so on, for 10% and 12%.

Figure 4.38 can be used to read the loss of slump by adding a certain percentage of fibres and the modulus of rupture gained by introducing the latter.

In order to give examples of how to use the results of the workability strength investigation, Figure 4.39 and 4.40 were drawn.

Figure 4.39 relates the slump of the mix to the percentage by weight of fibre added to it. Each curve is identified by the w/c ratio used in the mix. The slump was chosen instead of the V-B time because as already mentioned, it is easy to carry out on site and gives sensitive results with the melt extract steel fibres.

The modulus of rupture is plotted against the slump of each mix (Figure 4.40). Each curve is drawn with its mix name and the slump at 0% of the fibre of the mix is between brackets.

Figure 4.39 shows that the slump can vary from 0 to 75mm, and the percentage of fibre by weight of the matrix can vary from 0 to 10% (to 12% in the case of the mortar) in the mixes.

In Figure 4.40, the M.O.R. varies from 4.93 N/mm^2 to 10.40 N/mm^2 and the slump varies from 0 to 75mm.

Then in order to use the workability strength investigation, the slump, fibre percentage and M.O.R. must not exceed the upper and lower values of Figures 4.39 and 4.40.

i) Example 1

Assuming we want an M.O.R. of 9 N/mm^2. Figure 4.40 gives us the different choices (Table 4.2).

ii) Example 2

If we want a slump of 25mm, Figure 4.40 gives us the different mixes and their corresponding M.O.R.'s. Figure 4.39 gives us the corresponding fibre percentage and w/c ratios.

iii) Example 3

Suppose we want to know what are the corresponding M.O.R.'s

Table 4.1 The modulus of rupture percentage increases in the different mixes for a fibre inclusion of 10%.

MIX TYPE				aggregate/ cement ratio	Percentage increase
O.P.C.	Sand	10mm aggregate	20mm aggregate		
1	2.4	-	-	2.4	26*
1	2	2	-	4	40 - 50
1	2	3	-	5	70 - 80
1	1.5	1.5	-	3	30 - 40
1	1.5	0.5	1	2	27
1	1.5	0.83	1.66	4	38

* Increase of 12% fibre inclusion.

Table 4.2 The different choices of mixes related to an M.O.R. of $9N/mm^2$.

Different mixes that can be chosen	Slump(mm) obtained	% fibre by weight matrix
mix A(w/c= 0.36)	15	11
mix B(w/c= 0.36)	0	8.5
mix C(w/c= 0.408)	0	7.5
mix D(w/c= 0.2857)	11	6
mix D(w/c= 0.2971)	8	9
mix E(w/c= 0.2886)	2	8.5

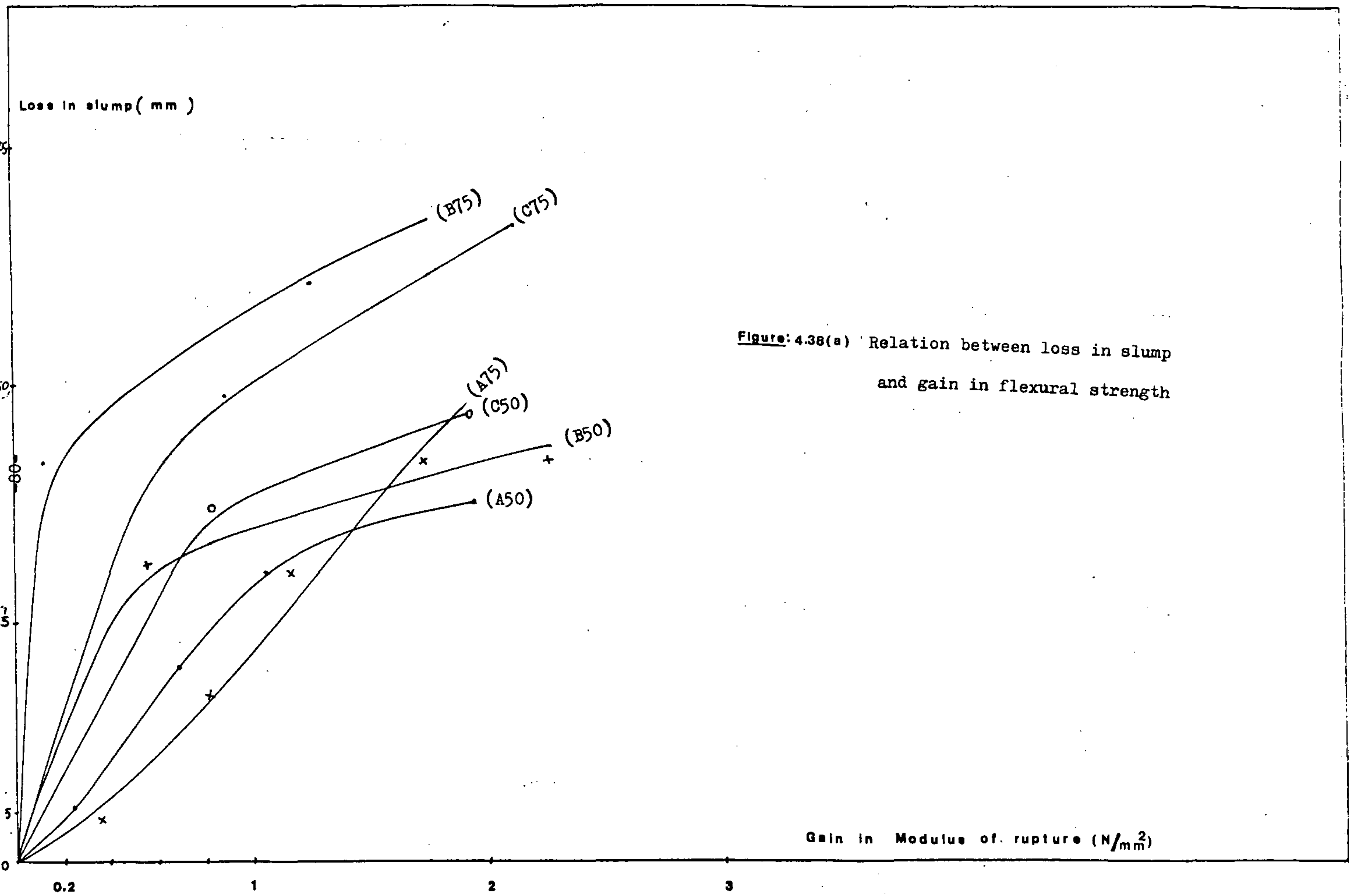


Figure: 4.38(a) Relation between loss in slump and gain in flexural strength

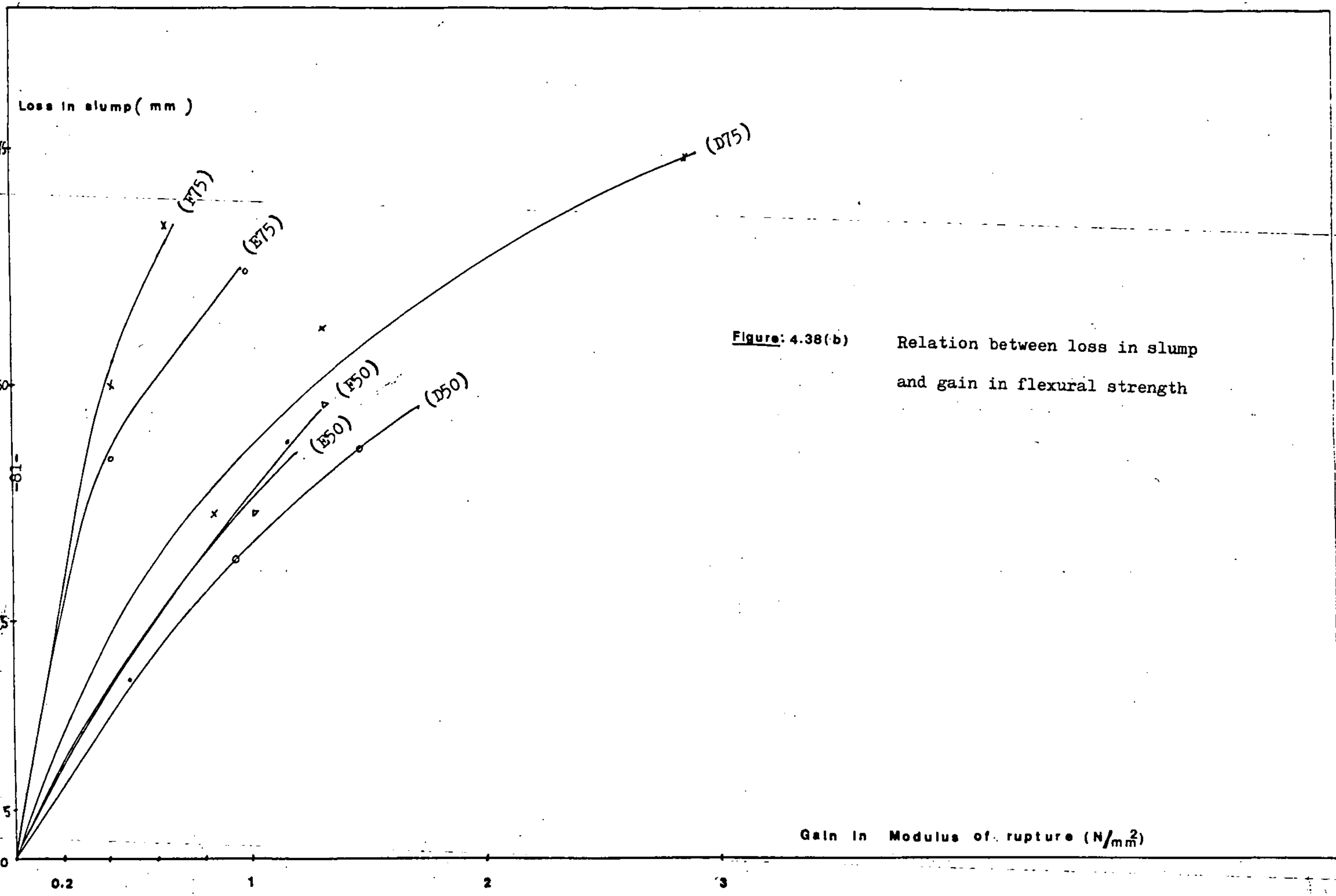
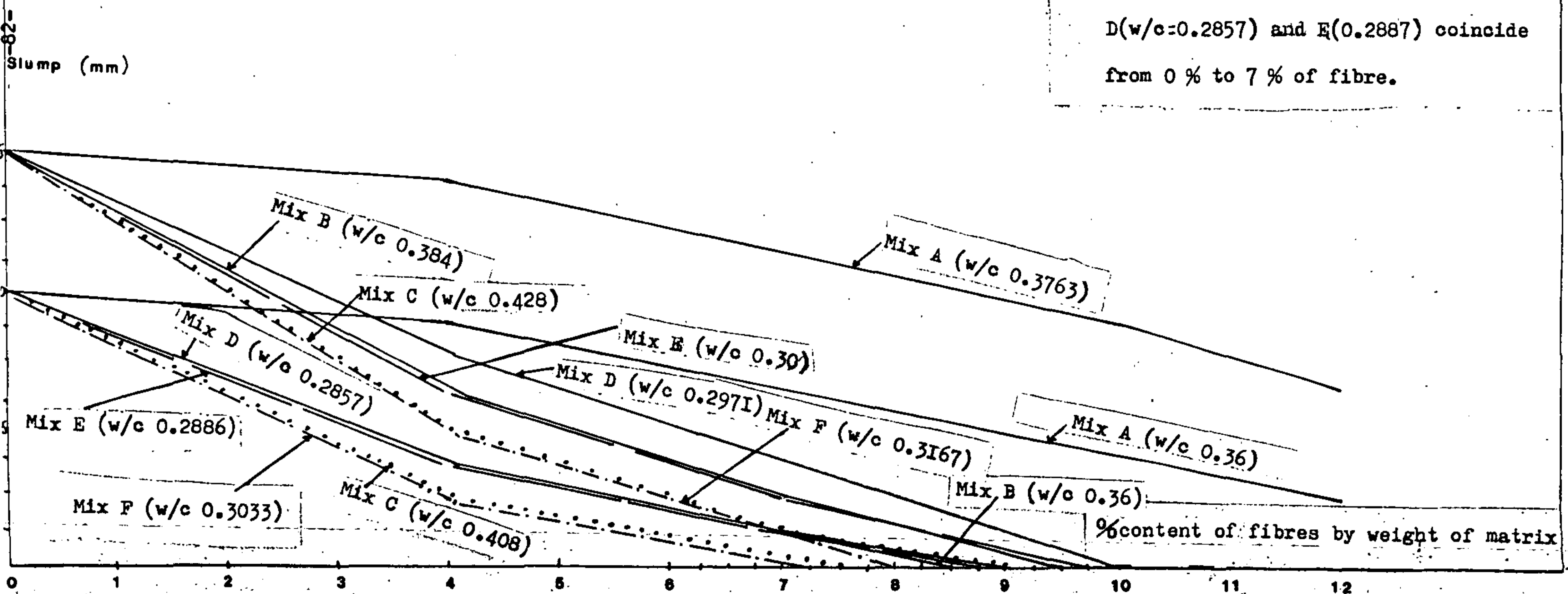


Figure: 4.38(b) Relation between loss in slump and gain in flexural strength

The effect of fibre contents on slump of fibre reinforced composites

Figure:4.39



N.B. The curves of mixes B(w/c=0.36), D(w/c=0.2857) and E(0.2887) coincide from 0 % to 7 % of fibre.

Figure: 4.40 (a)

Relationship between modulus of rupture and slump

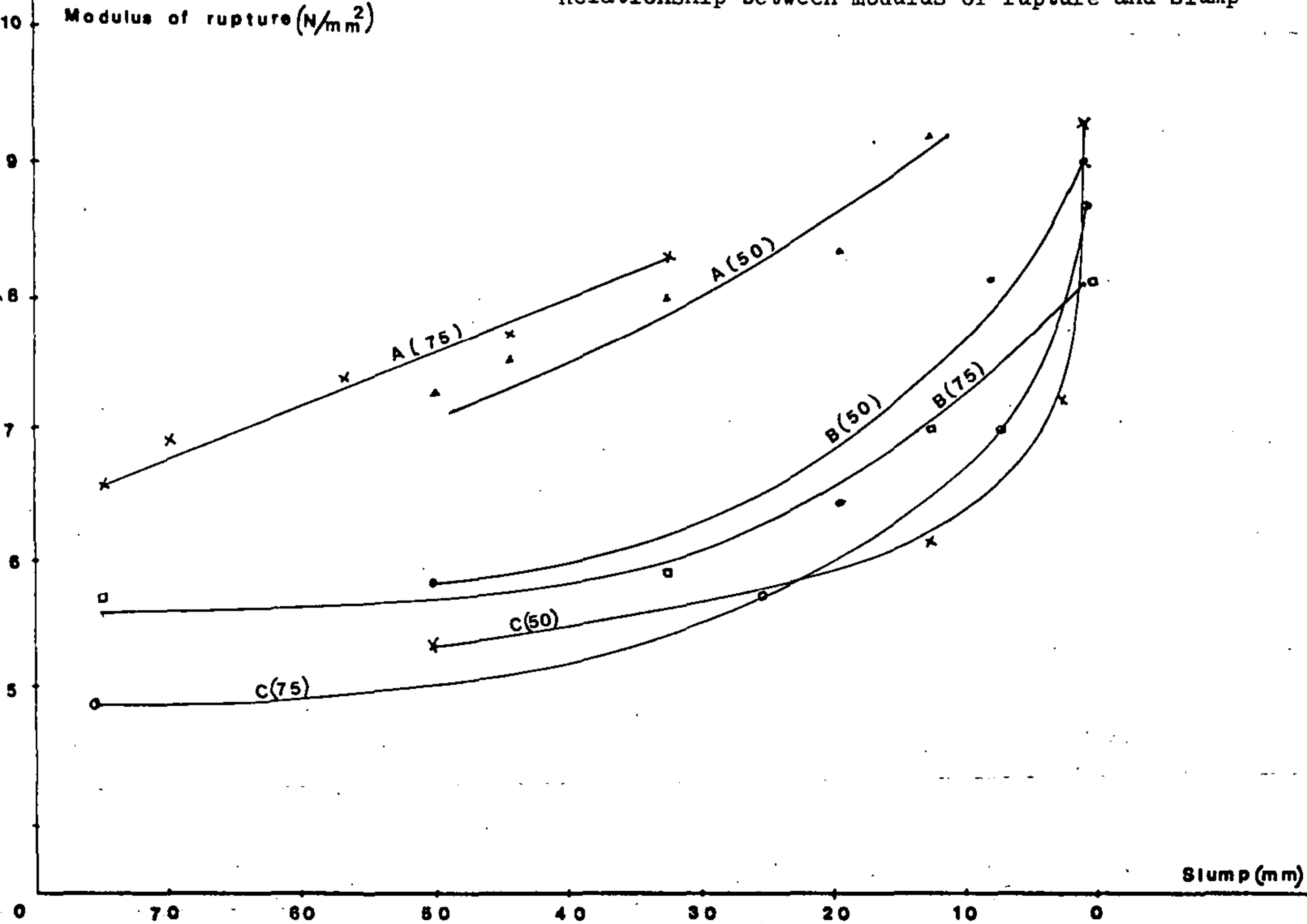
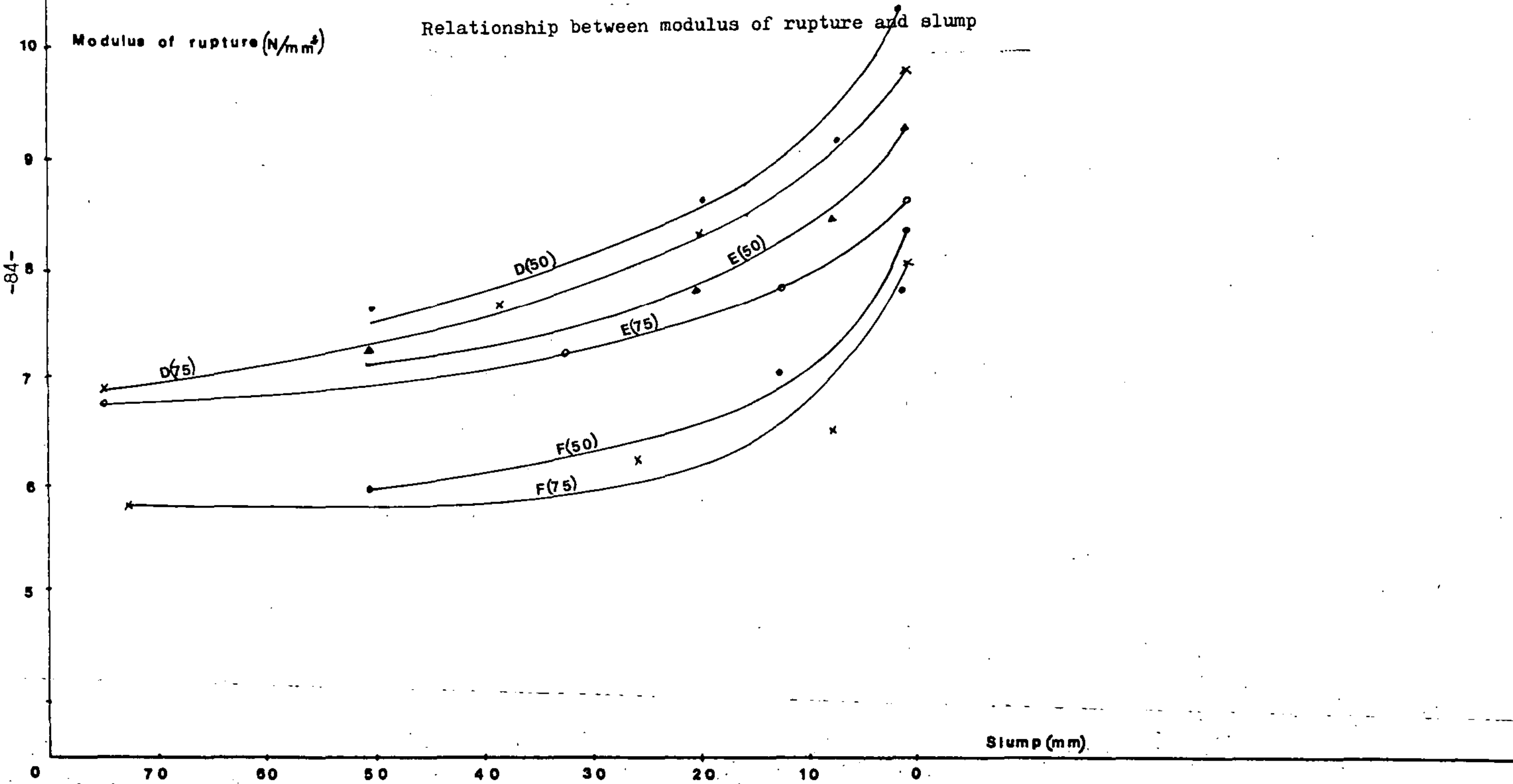


Figure: 4.40(b)

Relationship between modulus of rupture and slump



of a particular mix by adding 4 % fibre by weight of the matrix. For that , Figure 4.39 gives us the corresponding slump. Knowing the slump, Figure 4.40 tells us the M.O.R.'s for the particular mix with its w/c ratio.

By using Figures 4.39 and 4.40 we can obtain other information, such as , if we choose the fibre percentage and the M.O.R. we want, we can find the mix (or mixes) which gives us this M.O.R. and its slump.

N.B. 0.85l of Conplast 337 / 50kg of cement is added to every mix.

SECTION TWO Melt extract and D-form fibres in thin sheet cement composites

CHAPTER FIVE : MELT EXTRACT STEEL FIBRES IN THIN SHEET COMPOSITES

Although glass fibre reinforced cement (G.R.C.) is relatively new construction material its application is limited due to the reduction of its strength with time and its relatively high price.

In this chapter an attempt is made by using melt extract steel fibres in thin sheets aiming to replace the glass thin sheet composites. To do so, the investigation is carried out to determine the effect of the fibre content on rich cement matrices such as those used in G.R.C. mixes. High fibre percentage by weight of matrix were added into the mixes due to the good workability of the melt extract steel fibres. Long term strength is expected due to their stainless composition.

5.1 Theoretical behaviour of fibre reinforced cement in bending

It is likely that any structural element would be designed to act in flexure. Hence, a knowledge of how it would behave is vital before the behaviour in flexure can be understood.

Although fibre reinforced composites can be considered to be a fairly homogenous material in many respects, any attempt to analyse a beam in bending using elastic theory will show poor agreement with experimental results.

5.11 Analysis based on the tensile zone being simplified to a rectangular stress block

This simplification cannot be rigorously justified but considering the other indeterminate factors affecting the behaviour, the assumption will not cause much loss of accuracy.

The simple bending case is shown in Figure 5.1(A) where between the point loads there exists a constant bending moment of $\frac{FL}{6}$. Diagram B shows the stress and strain distributions down the depth of the beam, such that:

$$\text{Tension } (\varepsilon_T) = \varepsilon \text{ Compression } (\varepsilon_c)$$

$$\text{Tension } (\sigma_T) = \sigma \text{ Compression } (\sigma_c)$$

For the special case where the beam has a rectangular cross section of width B and depth D the extreme fibre stress or modulus of rupture is:

$$\text{M.O.R.} = \frac{FL}{BD^2} = \sigma_T = \sigma_{Comp} \qquad (1)$$

However, it has been found experimentally that the neutral axis rises up approximately to D/4 from the compression face (See 5.4).This results in a strain distribution like the one in Diagram C, and consequently the modulus of rupture as calculated above does not represent the extreme fibre stress in this case.

An analysis can still be carried out by assuming the stress distribution is as shown and σ_{cu} is the ultimate post cracking tensile strengths of the composites.

Refering to Figure 5.1(C):

For equilibrium $T = C$

$$T = \sigma_{cu} \times \frac{3D}{4}$$

The lever arm $L = \frac{1}{2} \cdot \frac{3}{4} D + \frac{2}{3} \cdot \frac{D}{4} = \frac{13}{24} D$

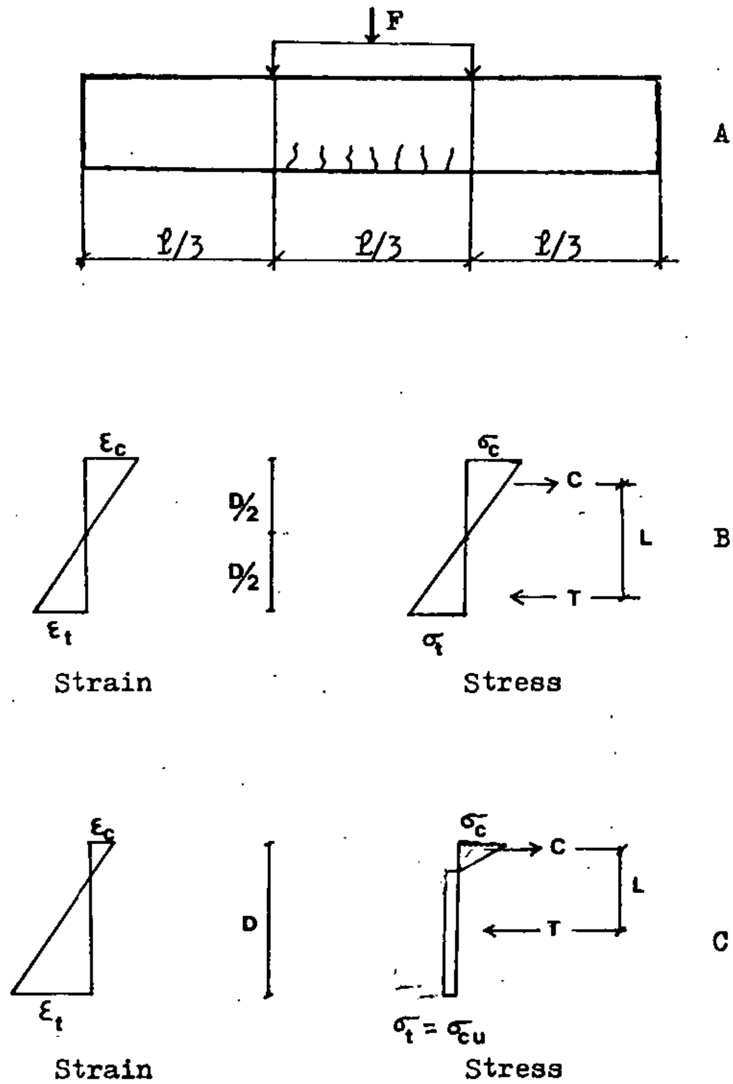


Figure:5.1 The stress and strain distribution for both elastic and non-elastic beams in flexure

Therefore the moment of resistance:

$$= \sigma_{cu} \frac{3}{4} D \frac{13}{24} D$$

$$= \sigma_{cu} \frac{13}{32} D^2 \qquad (2)$$

Using the same argument for the strain distribution of Figure 5.1(B)

$$T = C$$

$$T = \frac{\sigma_T}{2} \frac{D}{2} = \sigma_T \frac{D}{4}$$

$$L = \frac{2}{3} D$$

The moment of resistence $= \sigma_T \cdot \frac{D^2}{6}$ (3)

Equating equations (2) and (3) so that the two beams should have the same strength,

$$\sigma_T \frac{D^2}{6} = \sigma_{cu} \frac{13}{32} D^2$$

$$\therefore \sigma_{cu} = 0.41 \sigma_T \qquad (4)$$

This means that for so long as the post cracking flexural strength of melt extract fibre composite is greater than 0.41 σ_T then flexural strengthening will take place.

If σ_{MR} , the modulus of rupture calculated from elastic theory is substituted for σ_t , in equation (4).

$$\sigma_{MR} = 2.44 \sigma_{cu}$$

Thus, when the modulus of rupture is calculated for melt extract fibre composite from a flexural test, it is found to be two to three times greater than the strength in direct tension.

The limiting case is when the neutral axis actually reaches the compression face which yields:

$$\sigma_{MR} = 3.0 \sigma_{cu}$$

However, this could not be achieved exactly in practice, becaus the beam would fail in compression first.

The accuracy of using equation (2) depends on whether the neutral axis is at $\frac{D}{4}$ from the compression face, and on whether the rectangular tensile stress block is a realistic approximation to the actual distribution. The work done in 5.4 does suggest that both these assumptions are reasonably correct.

5.2 Preparation and testing of melt [illegible] extract steel fibres in thin sheet composites

For the materials used for mix design : Fibres, sand, O.P.C., water and mixing procedure, mixing technique, compaction, stripping, curing, see Chapter Three.

No additives were added to the mix and the mix proportions used are shown in Table 5.1.

The test beams were cast in three different moulds of internal dimensions: 234mm × 50mm × 12mm, 166mm × 50mm × 8mm and 132mm x 50mm × 6mm beams. Due to the important differences in flexural strength obtained by changing testing parameters, the width of all specimens was kept constant at 50mm and the span /depth ratio was also kept constant, equal to 17 (the distance between the external rollers of the rig were 30mm less than the beam lengths).

The specimins were tested at fourteen and twenty-eight days on the smooth face in tension and in compression. With each percentage of fibres added to the mix five specimens were tested. With the mix design 3:1, 12%, 14% and 16% fibre by weight of the matrix were added whereas with the mix design 2:1 only 12% and 14% were added due to the difficulty encountered in the workability by adding 16%.

Table 5.1 Mix proportions used in the melt extract fibre thin sheet composites

Weight of the mix constituents		W/C ratios
Cement (O.P.C.)	Sand	
3	1	0.311
2	1	0.325

The water/cement ratios were the ones which gave 75mm slumps withou fibres. For each test five beams were cast and tested.

5.3 Mechanical properties of fibre composites

5.31 Orientation of the fibres

This is an extremely important factor controlling the properties of the material. The fibres may be orientated in any one of three main ways:

i) Uni-directional.

ii) Random planar.

iii) Random three-dimensional.

These are illustrated in Figure 5.2

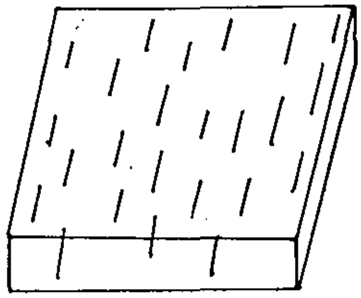
Since the sheets are relatively thin and flat with the requirement to resist bending in both the major axes the planar 2-D orientation is used.

When examples of material properties are quoted in this chapter the fibre orientation is a random 2-dimensional array.

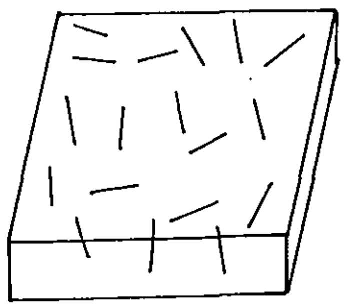
5.4 Behaviour in flexure

Since the direct tensile test is very difficult to perform accurately, the four point bending test has now been adopted as the standard measure for strength, However, since fibre composites are composite materials, the results of such a test require careful evaluation.

H.G. Allen[27] of Southampton University did a considerable amount of experimental work on the behaviour of glass fibre reinforced laminates in 1971. A precis of the work he undertook is give below and some of his conclusions.

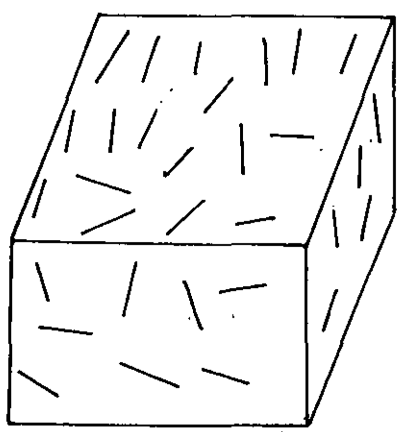


i) Uni-directional



ii) Random planar

Figure:5.2 The three main fibre orientations.



iii) Random 3-dimentional

5.41 Experimental results

The experiments were carried out twice, once on beams with the smooth side in tension, and secondly with the smooth side in compression.

In Figure 5.3, these results have been averaged to produce a single set for both the compressive and tensile faces of the beam. Up to a strain of approximately 400×10^{-6} both the tensile and the compressive extreme fibre strains were approximately equal to linear. At this point, presumably cracking started on the tensile face and the curves began to flatten out.

The compressive curve rises more quickly, suggesting that the neutral axis is shifting towards the compressive face. This is of crucial importance in the analysis of flexural beams and will be dealt with in greater detail later. It implies that the modulus of rupture stress as calculated for an elastic beam does not truly represent the extreme fibre stresses. However , this need not detract anything from the value of the modulus of rupture as a convenient means of comparing different composites.

5.42 Theoretical prediction of results of bending tests

This approach is somewhat similar to the C.P.110 method of design for normal reinforced composites, and can be summarised in a series of steps:

i) Obtain the stress strain curves for the material in direct tension and compression. For the case of computation, these are best reduced to a series of straight lines such as the ones in Figure 5.4(A) and (B);

ii) Select a width and thickness for the specimen in flexure;

iii) With reference to Figure 5.4(C) it has been found from experience

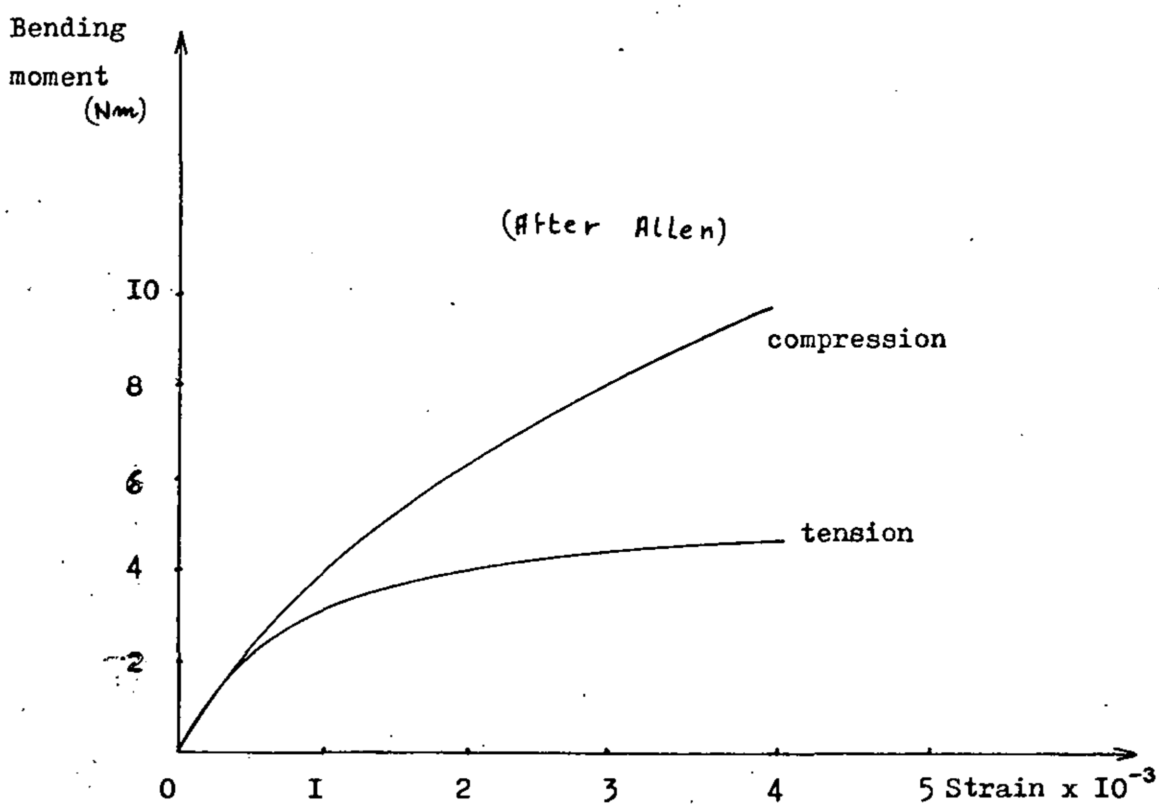
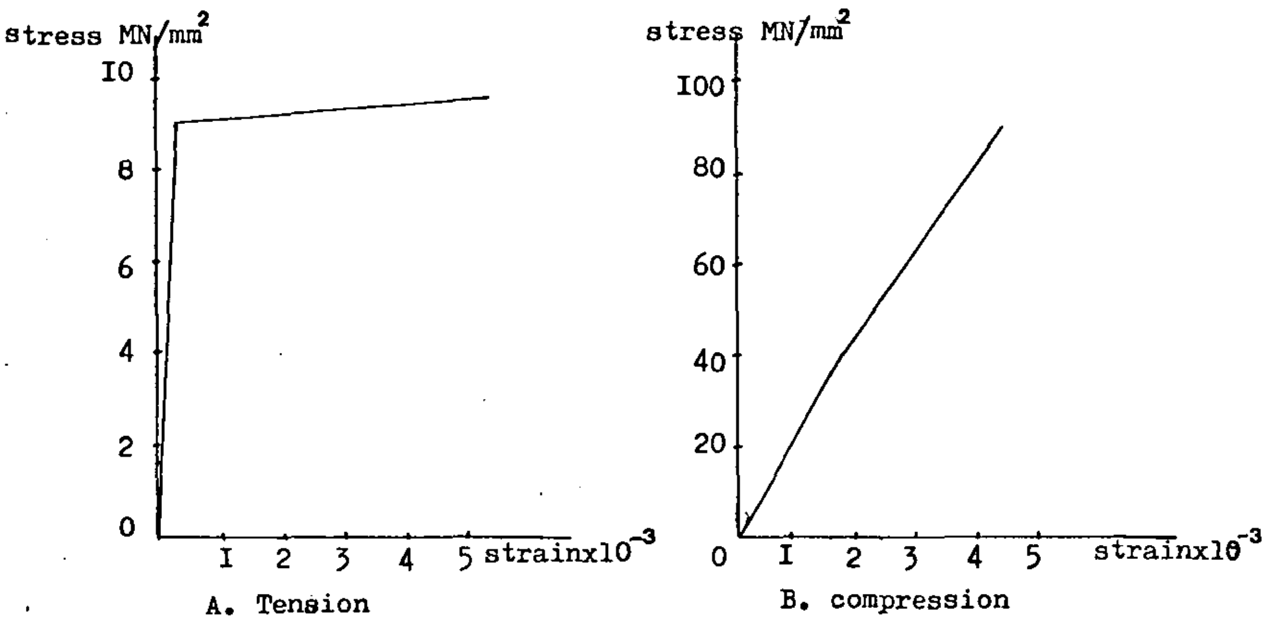
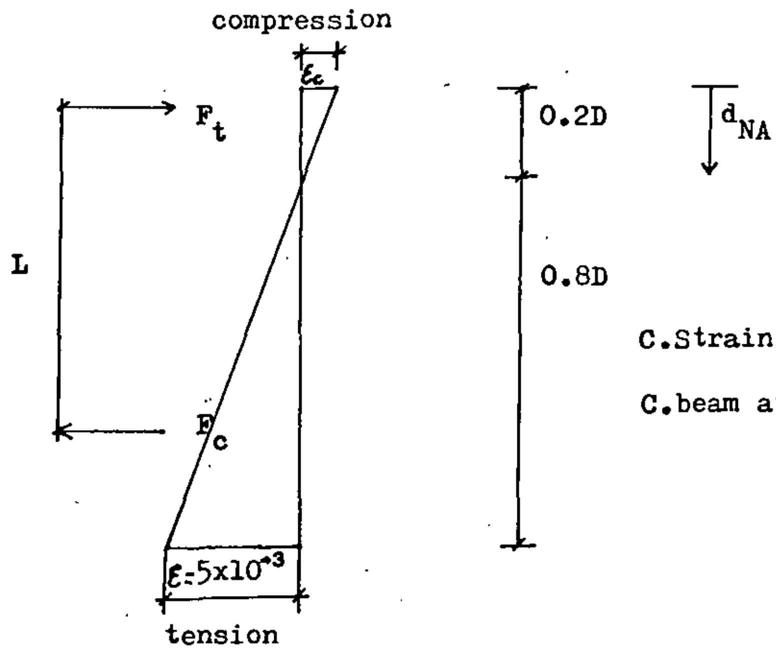


Figure:5.3 The extreme fibre strain on the compressive and tensile faces of the beam against the applied bending moment.





C.Strain distribution down a G.R.

C.beam at failure.

Figure:5.4 The idealised stress/strain distributions for G.R.C. in direct tension and compression,and the strain distribution throu a beam in flexure.

that at small bending moments the neutral axis is d_{NA} from the compression face, where d_{NA} is approximately $\frac{d}{2}$. As the bending moment is increased the neutral axis rises to about $\frac{d}{5}$, from the compression face. This result has also been shown by Edgington[23] for steel fibre reinforced concrete. The distance d_{NA} provides a useful parameter linking the bending moment to the strain distribution. Hence, select an initial value for d_{NA} that is slightly less than $\frac{d}{2}$;

iv) Assuming a linear distribution of strains through the beam, gives an $\mathcal{E}_c$ and hence obtains the strain distributions. Using the stress strain distribution down the section, we can calculate the forces F_t and F_c that are acting;

v) The initial guess for $\mathcal{E}_c$ must now be adjusted, d_{NA} being kept constant, until F_t equals F_c so that the section is in a state of pure flexure. The bending moment equals F_cL or F_tL;

vi) The steps iii) - v) may then be repeated until an entire range of bending moments has been covered.

This iterative process is obviously best suited to putting on a computer, and hence printing out values of extreme fibre strains and stress distributions through the section for various bending moments.

When the results of the above calculations were compared with those obtained experimentally(Figure 5.3) an excellent agreement was obtained considering the natural variability of the material under test.

One point worth noting is how the very sharp discontinuity of Figure 5.4(A) has become rounded in Figure 5.3. This means that "the bending test is a very insensitive measure of the point where cracking first occurs".[28]

Allen calculated a bending strength of 21.0 MN/mm^2 which compared with the values 20.9 - 27.6 MN/mm^2 which he obtained experimentally. Although these may not be considered as excellent results by normal standards, they are about as close as can be expected with composite materials such as G.R.C.

This piece of research is based on an assumption about the position of the neutral axis at failure, which can be proved experimentally.

5.43 Effect of the fibre percentages on the modulus of rupture

Within the limits of experimental error, the M.O.R. increases with increasing fibre content until an optimum is reached, after which the M.O.R. should decrease.

5.5 Experimental work

With the ratio span/depth kept constant at seventeen, the test rig was capable of breaking the three different beams.

Using the information gathered from the experiments, the modulus of rupture (M.O.R.), the limit of proportionality stress (L.O.P. the Youngs modulus and the toughness index were investigated.

5.51 Description of the test rig used for the investigation

I used a test rig of the laboratory which I developed for my own experiments.

A side elevation of it is shown in Figure 5.5 and it consisted basically of two strong steel channel sections designed to fit on the Instron TT T-B testing machine, with the provision for four rollers that act as the loading points for the beams. To ensure that no axial thrust developed in the beams, each roller was fitted with needle bearings to minimise the friction. They were also able to

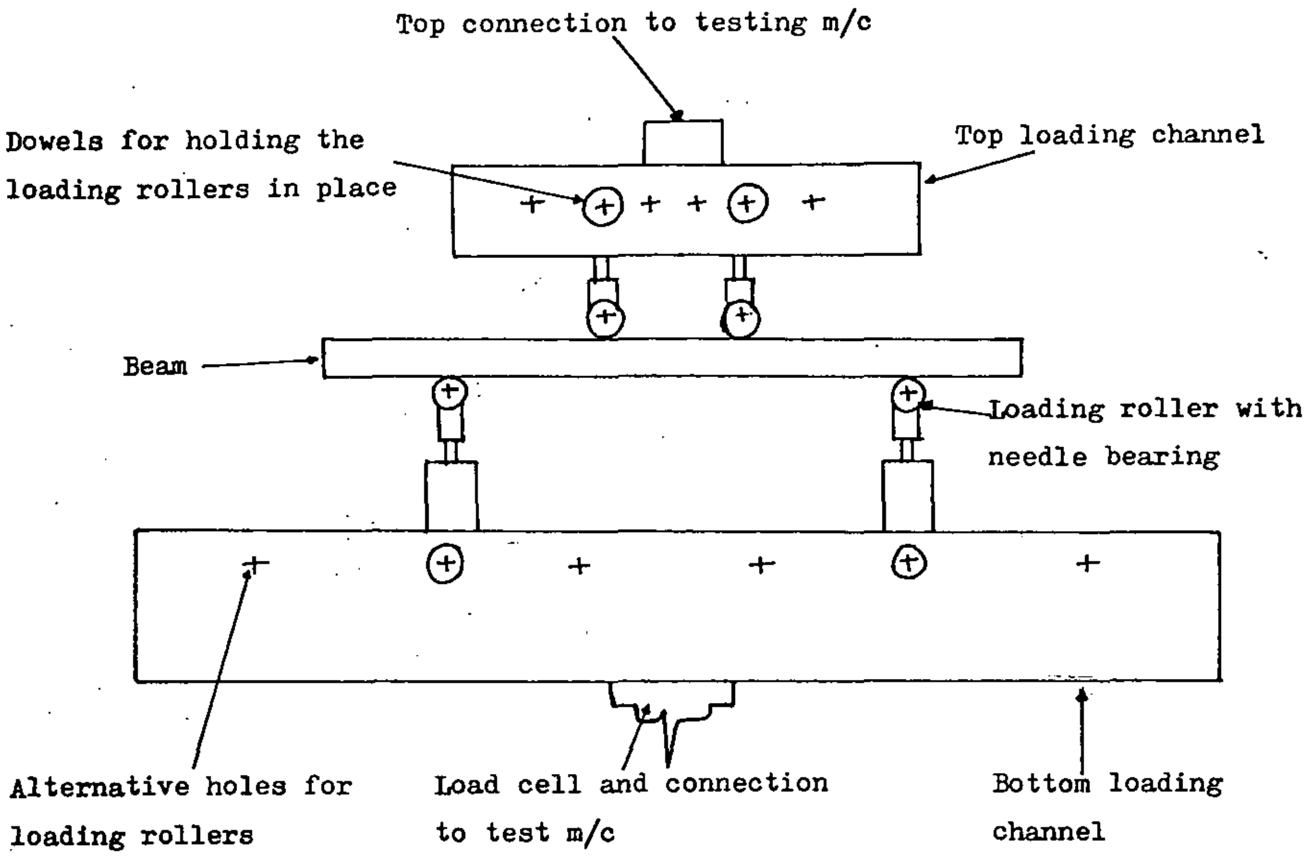


Figure:5.5 Side elevation of the rig used for the flexural tests tilt within their own plane to accomodate uneveness across the width of the specimen.

Plate 5 shows how the rig fitted into the machine and how the beams were tested. The total applied load was measured as the reaction from the base of the rig via an electrical load cell.The output from the cell was amplified by the machine and diaplayed on the Y-axis of the plotter. The deflections were measured by a "linear variable differential transformer" (L.V.D.T.) with a 10mm travel. As the base was extremely rigid, this gave a good indication of the deflection of the centre of the beam.

The rig had been designed so that by pulling out a dowel each roller could be moved to a new position and fixed by inserting the dowel back through the appropriate hole.

The output from the L.V.D.T. was passed to the X-axis of the plotter via an external amplifier so that load/deflection curves could be plotted.

5.52 Conducting the flexural testing

Before any testing could be carried out, the equipment had to be calibrated so that both the load and deflection traces on the X-Y plotter had convenient scales.

i) Calibrating the graph plotter for load;

The testing machine had its own graph plotter capable of displaying load on the X-axis and time on the Y-axis. As a force was applied to the load cell so the stylus moved, and this was calibrated using dead weights.

To calibrate the internal plotter, the machine was set to the lowest range and test rig removed from the load cell. The stylus

Plate:5 The Instron TT-B testing machine with the test rig in position could then be zeroed before applying a known weight to the cell. Using the calibration control, the pen could be moved so that it registered the correct load.

The machine could then be switched to its operating range, say 1000 lbs, and an artificial "load signal" applied to the internal plotter to give a full scale deflection. This would then represent an output signal equivalent to a load of 1000 lb., and the external plotter could then be calibrated against this signal to read as required.

The advantage of using the internal plotter as an intermediate in the calibration process was that it enabled small dead weights to be used to calibrate the machine for large forces.

ii) Calibrating the graph plotter for deflection;

A special micrometer jig had been constructed that enabled the L.V.D.T. to be moved by accurately measurable amounts i.e. 0.001mm

To calibrate the L.V.D.T., it was clamped into the micrometer and the external graph plotter zeroed on the Y-axis. The L.V.D.T. was then deflected by exactly 1mm and the stylus of the plotter adjusted using the sensitivity control until it was calibrated on a convenient scale;

iii) Controlling the rate of loading;

The machine was able to carry out the tests at a number of different crosshead speeds and I wanted to test each different length of beam so that its extreme fibre strain rate was content.

The deflection of a simply supported beam is

$$\propto \frac{P\,L^3}{E\,I} \propto \frac{P\,L^3}{B\,D^3}$$ where $P =$ applied load

$L =$ span of the beam

$E =$ Youngs modulus

$I =$ second moment of area about the bending axis

$B =$ width of the beam

$D =$ depth of the beam

Therefore, the cross head speed for each length of beam was made to be proportional to its $\frac{P\,L^3}{B\,D^3}$ value.

This resulted in the following cross head speeds being used, which were the ones available on the machine that were nearest to the calculated values

102mm	0.01" per minute
136mm	0.02" per minute
204mm	0.05" per minute

A consequence to this was that the testing time for each beam was kept virtually constant, despite the variation of its span.

5.6 Results and observations of the tests

Due to the high number of curves obtained from the tests only two typical curves have been included(See Figure 5.6)

All the reinforced beams have the same initial linear region with the smooth face in tension or in compression. In the case of the smooth face in tension the linear region is followed by a flatter curved section until failure. Whereas, for the beams tested with the smooth face in compression the linear region is followed by a relatively horizontal section with a lot of peaks until failure. The

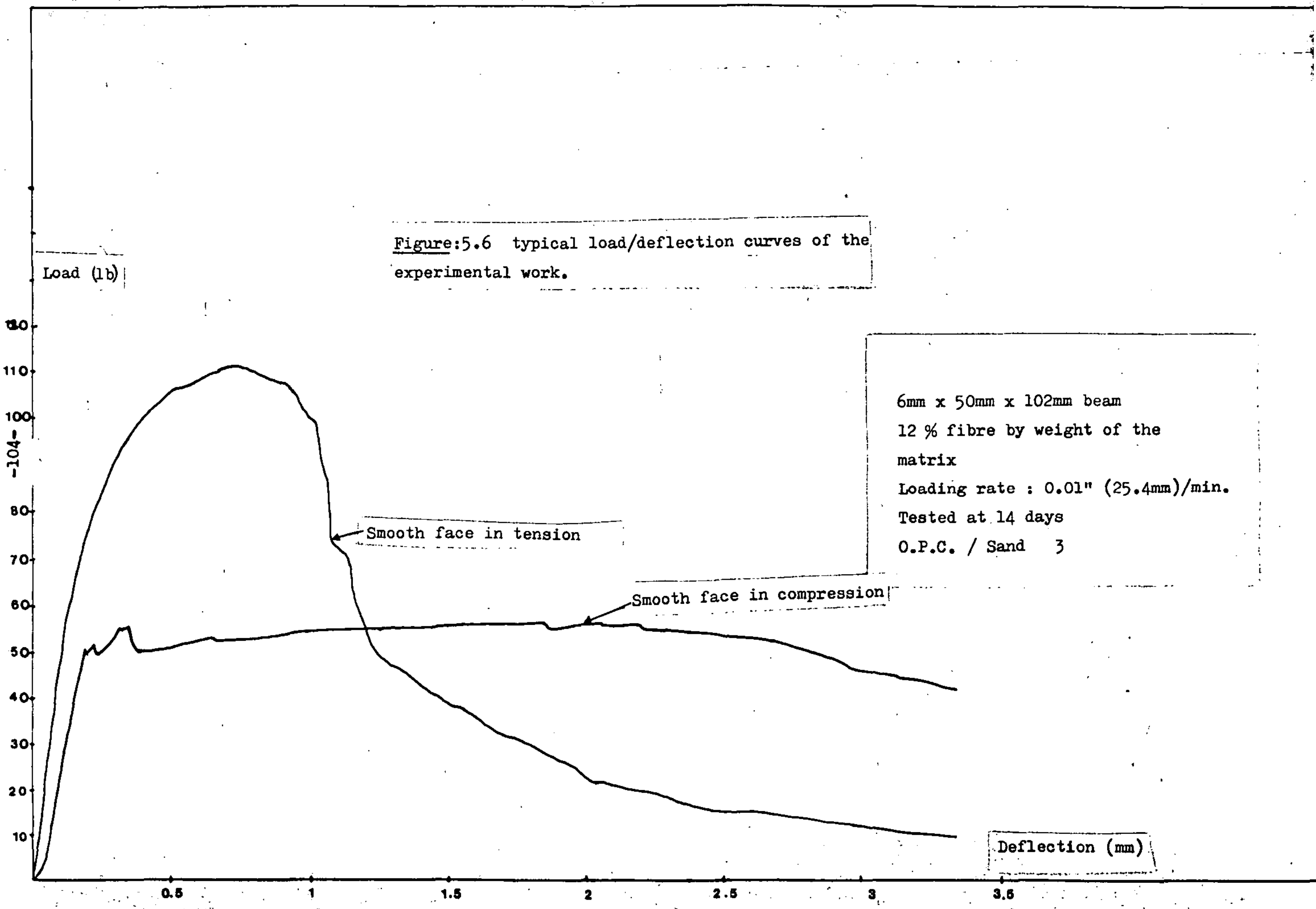


Figure:5.6 typical load/deflection curves of the experimental work.

unreinforced beams (tested for reference) had virtually the same initial linear region and broke without showing any ductility when tested on either face.

The beams broke at a right angle to their longest dimension. The cracking as generally accepted occured when the load deflection curve ceases to be linear.

It was obvious that most of the fibres pulled out but some had broken. From examining the broken ends of the beams, it was noticed that those fibres which had only a short length embedded on one side of the major crack pulled out. Those with a long length embedded on both sides sometimes broke.

Every beam broke in tension with no visible sign of spalling on the compression face.

5.61 Calculation of the modulus of rupture for a beam (M.O.R.)

For a uniform elastic beam of rectangular cross section loaded at the third point, the extreme stress, or modulus of rupture is given by:

$$\text{M.O.R.} = \frac{P\,L}{B\,D^2}$$

where P = total load applied to the beam

L = total span of the beam

B = breadth of the beam

D = depth of the beam

5.62 Calculation of the limit of proportionality stress (L.O.P.)

This is similar to the M.O.R. in that it is again the extreme fibre stress, but this time the load, P, used in the formula is the force at which the curve ceases to be linear. The method of determining this point is given in the section on toughness.

5.63 Calculation of Youngs modulus

In the steel designers' manual, the deflection at mid span for uniform beam loaded at the third point is given by:

$$d_{max} = \frac{23\ P\ L^3}{1296\ E\ I}$$ which can be rearranged to:

$$\text{Youngs modulus} = \frac{23\ P\ L^3}{1296\ I\ d}$$ where

P = load applied at L.O.P.
L = total span of beam
I = second moment of area
d = deflection at L.O.P.

5.64 Calculation of the toughness index

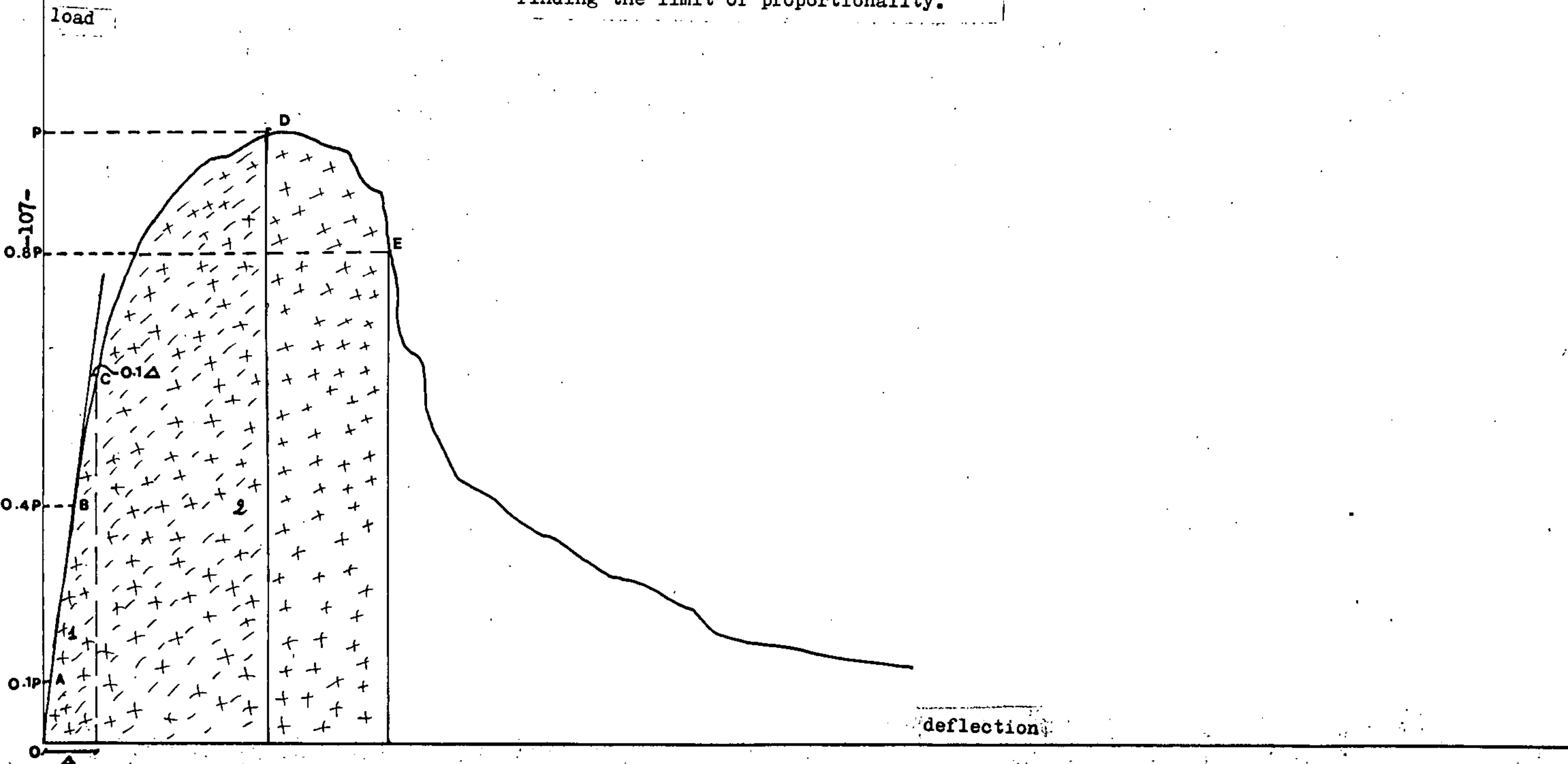
Figure 5.7 shows a typical load deflection curve and the arbitrary method chosen in order to locate the limit of proportionality. This point is not normally well defined because even the initial "linear region" is sometimes curved.

First the two points A and B were located at 0.1 P and 0.4 P respectively. Then, the line AB was produced forward and the limit of proportionality is defined as point C where the curve has deviated 0.1 Δ from AB. This arbitrary technique seems to work quite well.

The measure of toughness was arbitrary and was intended as a measure of the energy required to deflect the beam, compared with the energy required to bring it to the point of first crack.

Point D was defined as the point where the load is at a maximum and Point E was defined as the point where the load had been reduced to 80% of its maximum. Using a planimeter, the area of every curve was measured between the origin and Point C which is marked as area 1 , and between the origin and Point D and E which is marked as area 2 . The toughness index was then measured using the

<u>Figure</u>:5.7 a load deflection curve for the fibre reinforced beam with the method of finding the limit of proportionality.



maximum load criterion and 80% of the maximum load criterion. It was decided to use the two criteria in order to choose the one which gave the best results.

$$\text{Toughness index} = \frac{\text{area 2}}{\text{area 1}}$$

5.65 Results of the experiment

The mean results for every beam tested were included in Appendix 3. 90% confidence limit on the mean value were calculated assuming that the results were normally distributed. Figure 5.8 gives the curve results of the tests.

5.7 Discussion of the results

5.71 Effect of fibre content on the M.O.R. and L.O.P.

Figure 5.8 shows the values of M.O.R. and L.O.P. plotted against the fibre content.

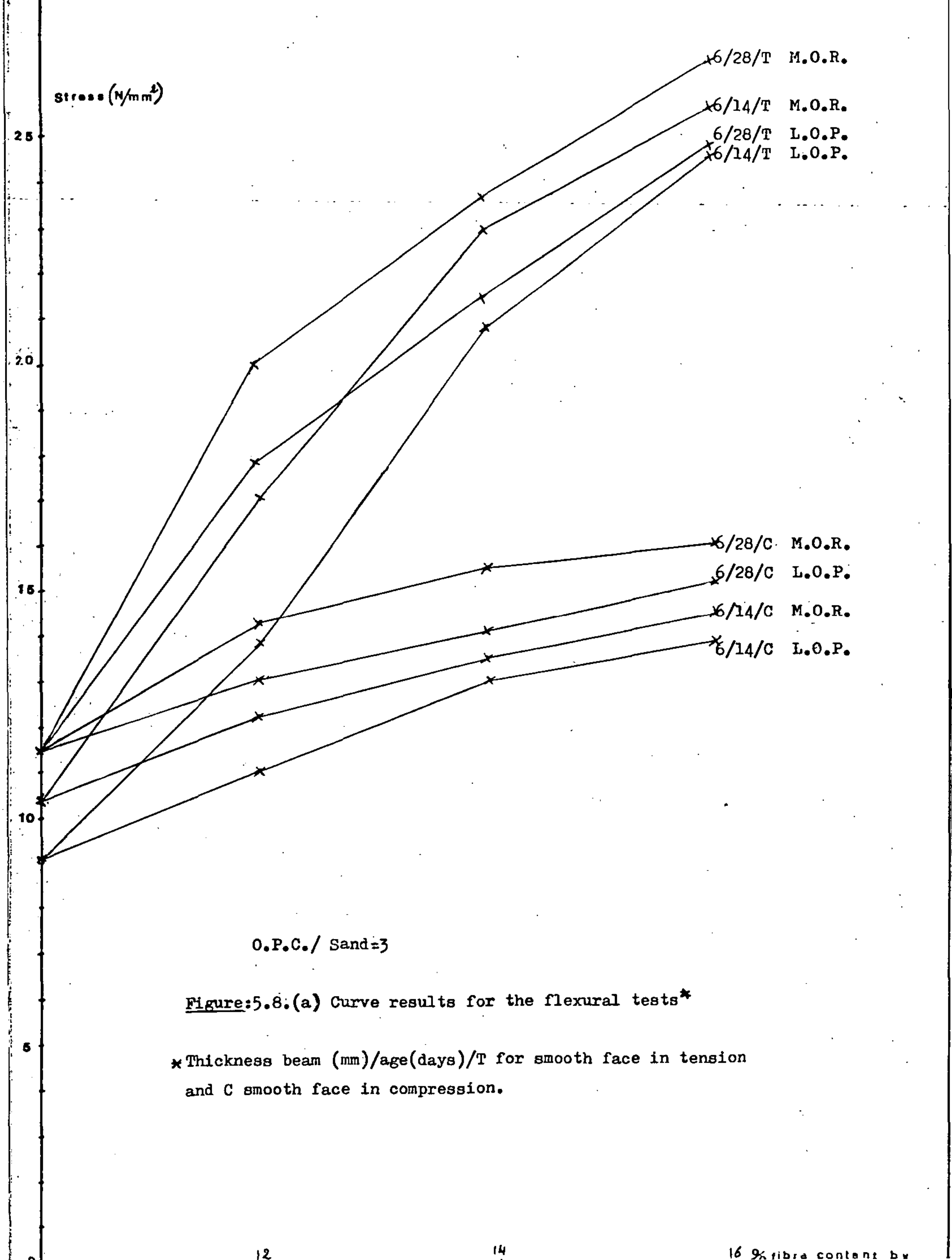
i) Smooth face in tension-matrix with ratio O.P.C./sand = 3;

The addition of 16% fibre by weight of the matrix more than doubles the M.O.R. and L.O.P. of the beams;

ii) Smooth face in tension- O.P.C./sand = 2;

The M.O.R. and the L.O.P. is increased by roughly 50% for the six and eight mm thick beams and only by 10% for the twelve mm thick beams when tested at fourteen days with an addition of 14% fibre by weight of the matrix.

At twenty eight days, the M.O.R. and the L.O.P. is increased by an average of 40% for the six and eight mm thick beams by adding 14% fibres by weight of the matrix. The former strength was only increased by 10% in the case of the twelve mm thick beams with the above percentage of fibre;



<u>Figure</u>:5.8.(a) Curve results for the flexural tests*

* Thickness beam (mm)/age(days)/T for smooth face in tension and C smooth face in compression.

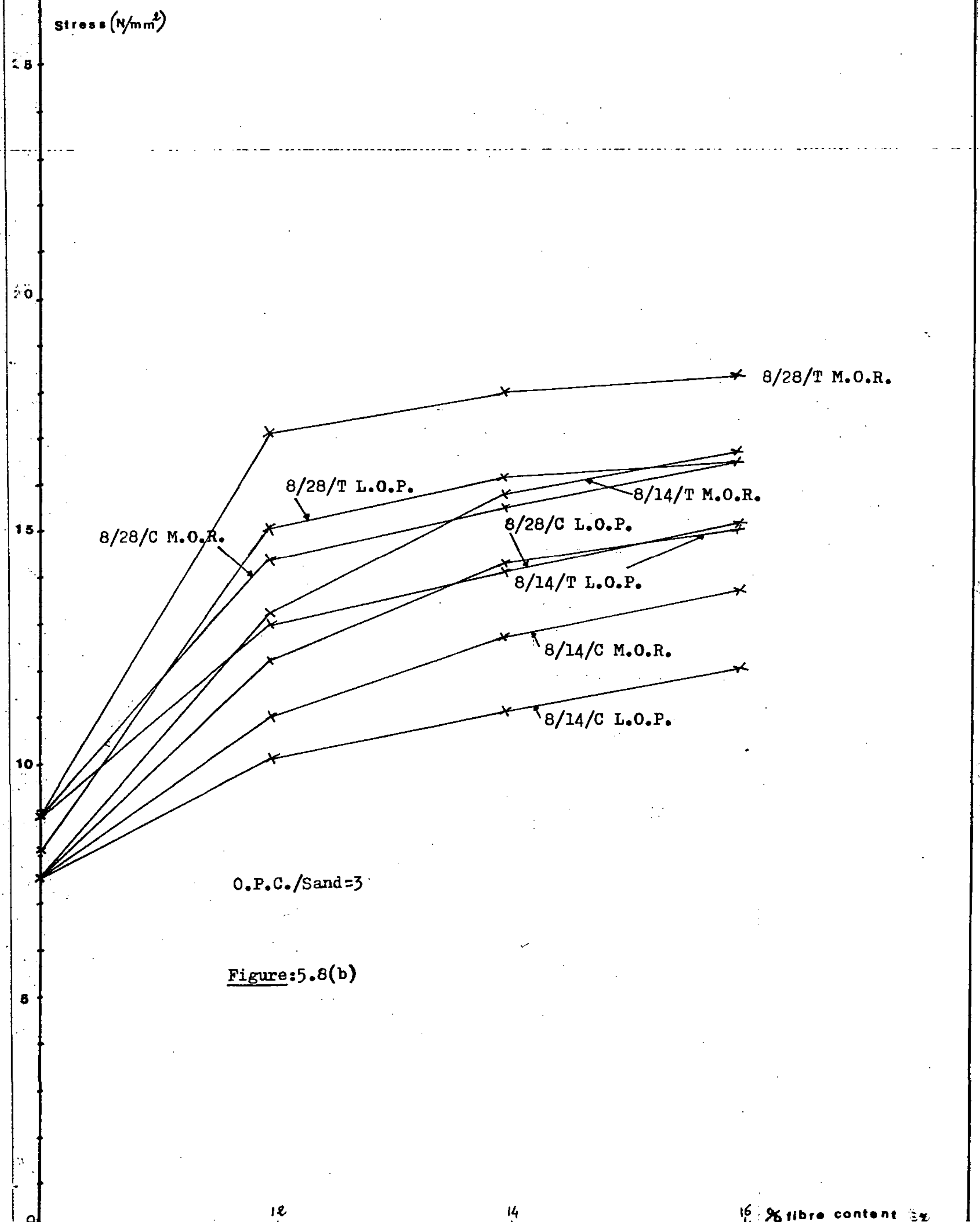

Stress (N/mm²)
25
20
15
10
5
0
12
14
16
% fibre content
8/28/T M.O.R.
8/28/T L.O.P.
8/14/T M.O.R.
8/28/C M.O.R.
8/28/C L.O.P.
8/14/T L.O.P.
8/14/C M.O.R.
8/14/C L.O.P.
O.P.C./Sand=3

Figure:5.8(b)

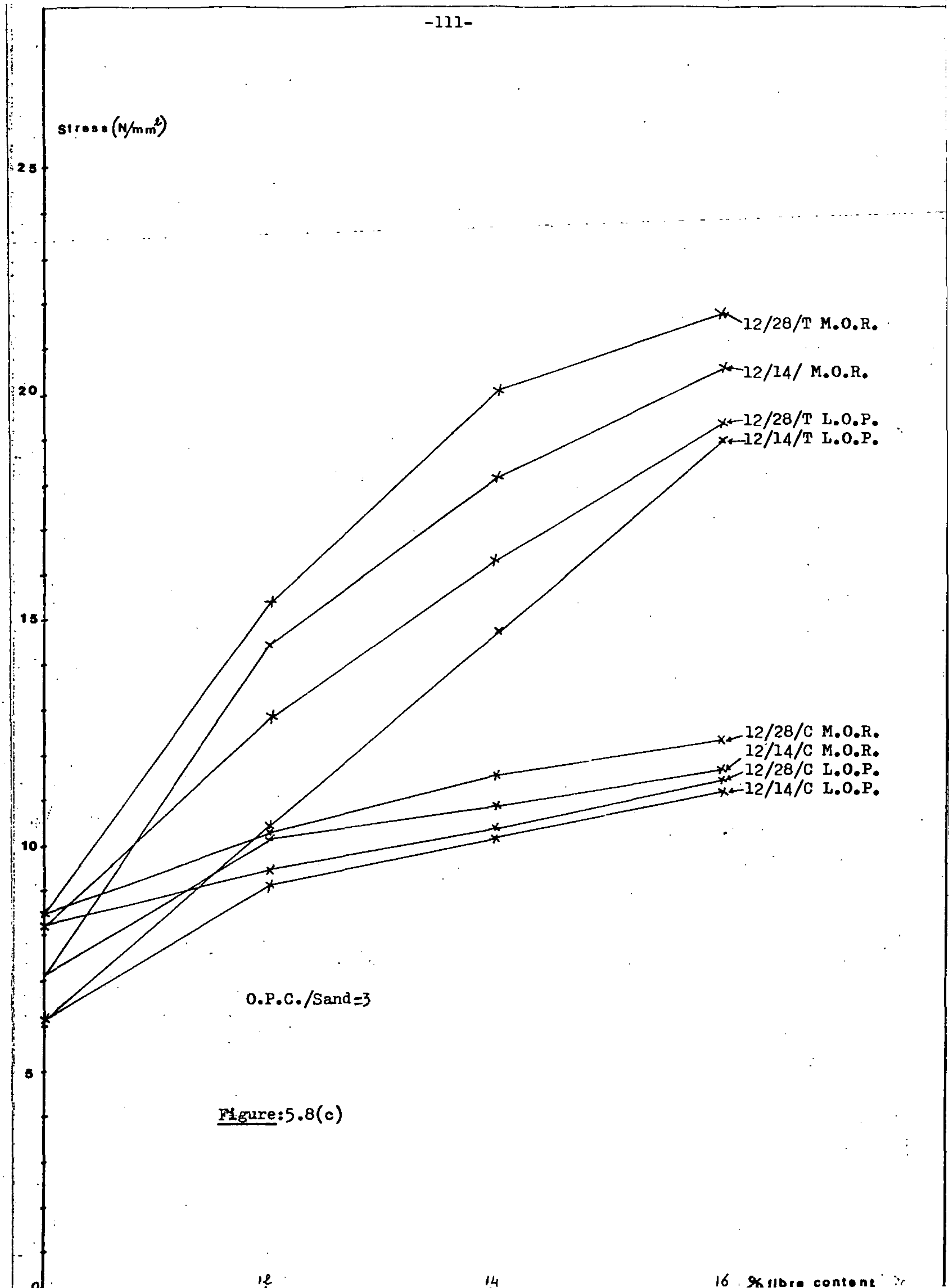
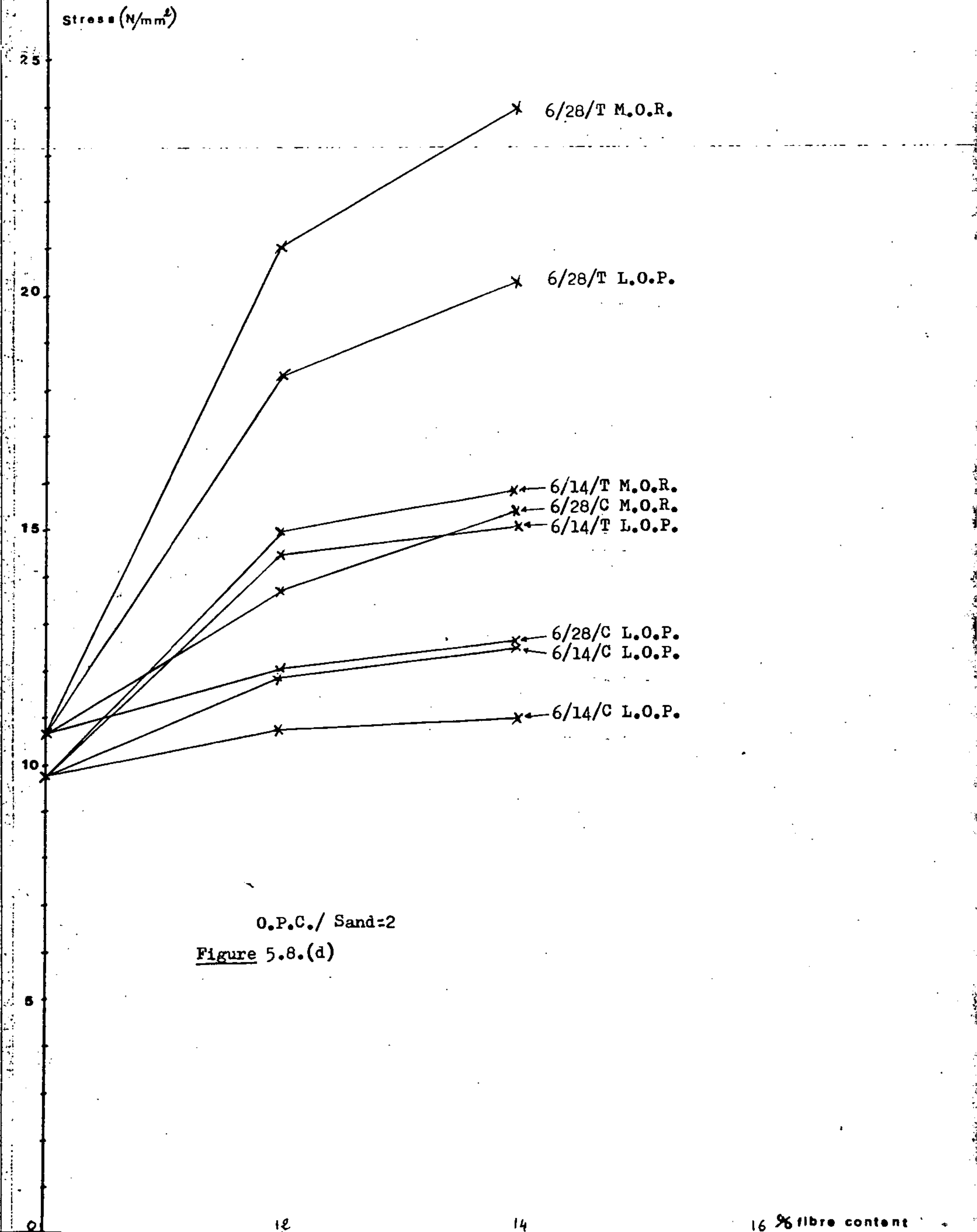

Stress (N/mm²)
25
20
15
10
5
0
12
14
16
% fibre content
12/28/T M.O.R.
12/14/ M.O.R.
12/28/T L.O.P.
12/14/T L.O.P.
12/28/C M.O.R.
12/14/C M.O.R.
12/28/C L.O.P.
12/14/C L.O.P.
O.P.C./Sand=3

Figure:5.8(c)



O.P.C./ Sand=2

Figure 5.8.(d)

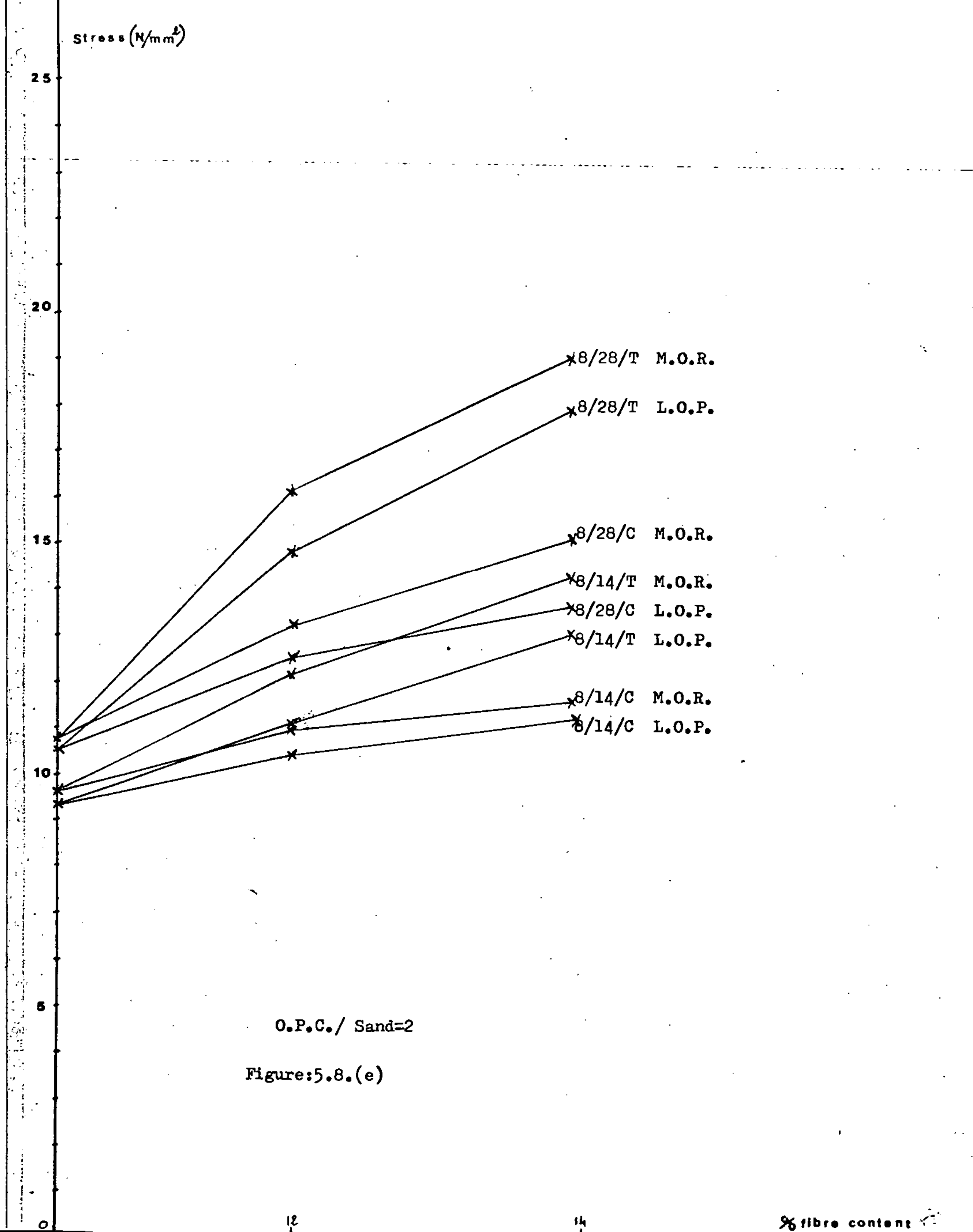
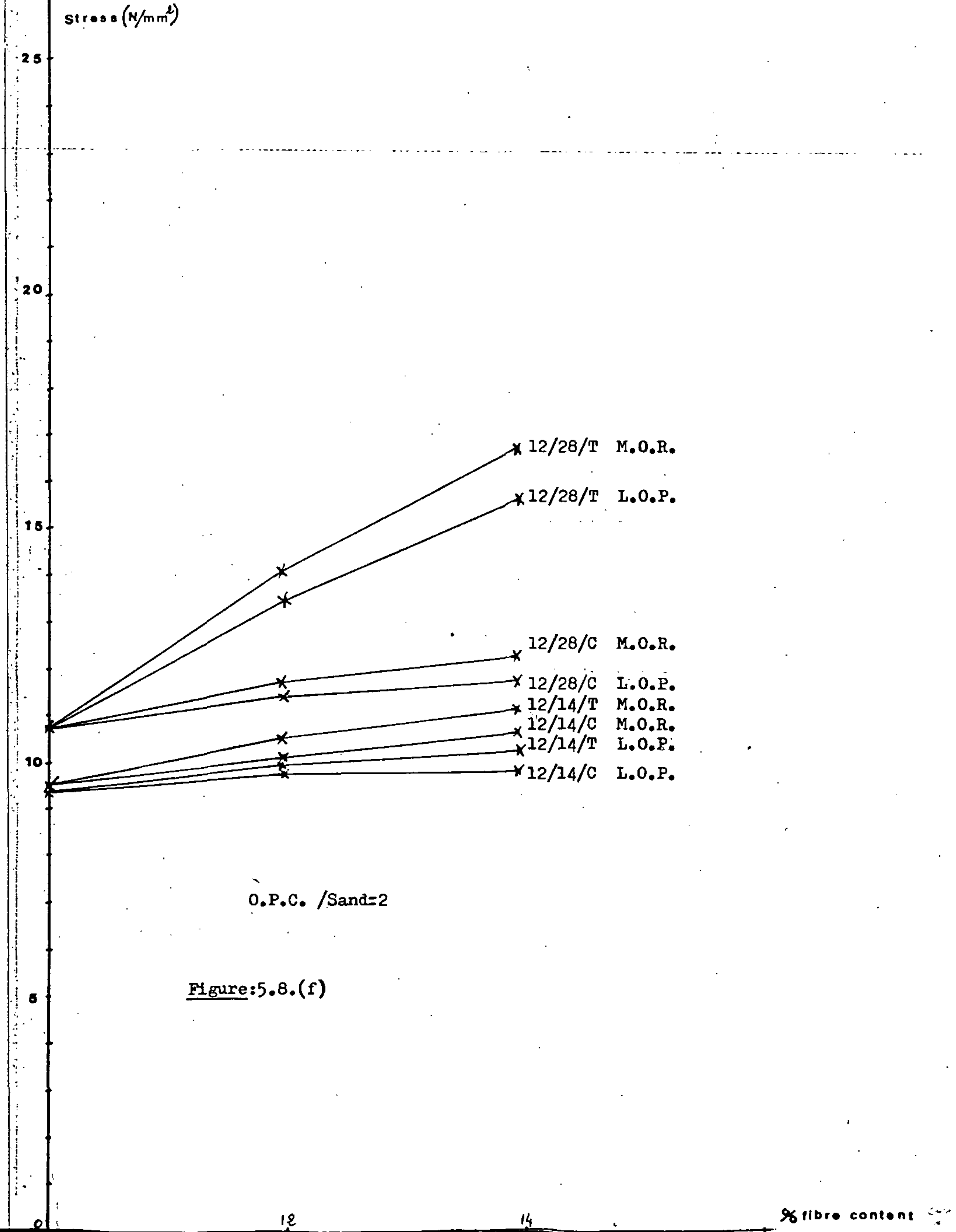

Stress (N/mm²)
25
20
15
10
5
0
8/28/T M.O.R.
8/28/T L.O.P.
8/28/C M.O.R.
8/14/T M.O.R.
8/28/C L.O.P.
8/14/T L.O.P.
8/14/C M.O.R.
8/14/C L.O.P.
O.P.C./ Sand=2
12
14
% fibre content

Figure:5.8.(e)



Stress (N/mm²)
25
20
15
10
5
0
12
14
% fibre content
12/28/T M.O.R.
12/28/T L.O.P.
12/28/C M.O.R.
12/28/C L.O.P.
12/14/T M.O.R.
12/14/C M.O.R.
12/14/T L.O.P.
12/14/C L.O.P.
O.P.C. /Sand=2

Figure:5.8.(f)

iii) Smooth face in compression;

The M.O.R. and L.O.P. are increased by an average which varies from 10% to 50% with both matrices, that is O.P.C./sand = 3 or 2

5.72 Effect of fibre content on Youngs modulus

The percentage of fibres in a mix have little effect on the Youngs modulus (see Table 2.1 of Appendix 2).

5.73 Effect of fibre content on the Toughness Index

Both the toughness indexes calculated by the maximum load criterion or by 80% of the maximum load criterion gave variable results so that it is difficult to deduce what the trends are.

5.8 Conclusions

i) The 90% confidence interval was quite high and variable. This means that the melt extract fibre composite is a variable material;

ii) The more fibre that was added the higher the modulus of rupture was obtained;

iii) The specimens gave higher strengths when tested on the smooth face in tension than when tested with it in compression. This was due to the relatively close presence of the fibres to the smooth face; the fibres tend to go down in the mould due to gravity;

iv) The richer the mix, the higher the strength achieved;

v) The thinner the beam, the higher were the M.O.R. and L.O.P.;

vi) A M.O.R. of over 26 N/mm^2 was reached with the six mm thick beam by adding 16% fibre percentage by weight of the matrix when tested at twenty eight days (O.P.C./sand = 3);

vii) Due to the stainless steel melt fibre and the strengths reached with the thin beams, it is possible to use it as a substitute to the G.R.C. components;

viii) The presence of melt fibres has increased the limit of proportionality significantly;

ix) The melt fibres have little effect on the Youngs modulus;

x) The flexure failure appears to occur by a combination of fibre breakage and pull-out, although the breakage does seem to occur at the major crack.

CHAPTER SIX : D - FORM FIBRES FOR CONCRETE COMPOSITES

As a result of great advances taking place in steel fibre technology a new fibre, known as D-form fibre , was developed in the United States. Whilst I was carrying out my research, I was lucky enough to receive a small amount of these fibres. I decided to include some investigations of these fibres in my research in order to study their characteristics and to draw some comparisons with the melt extract fibres.

6.1 Type of fibre

They have a cross sectional shape which resembles the capital letter "D" from which their name was derived.

If we assume that they were placed with the "D" end surfaces positioned as a written "D" they were crimped along a horizontal axis in a zig-zag form with rounded bends due to their thickness (see Plate 6).

As for most other fibres they were produced in different lengths. Each bit of the zig-zag measures around three mm in length and the angles of the bends are around 150°. They are mild steel fibres made of scrap material which gives them a lower cost over their contemporary fibres.

6.2 Tests carried out on D-form fibres

Since I only received a very small amount of D-form fibres, it was only possible to carry out a few tests. I used the fibres twenty five mm in length as crack arrestors (see Chapter 7), the thirty eight mm fibres in thin sheet composite and the fifty mm in the workability strength investigation.

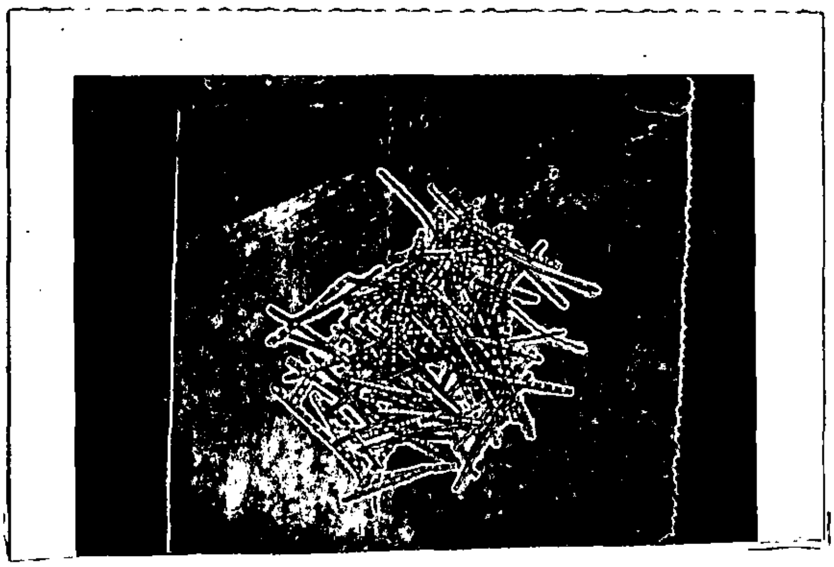


Plate:6 The D-form fibres

6.21 Workability strength investigation

For mixing procedure, mixing technique, compaction, stripping, curing and testing see Chapter 3.

To assess the effect of the D-form fibres on workability the V-B and slump tests were carried out as for the melt extract fibres on the mix designs 1:2.4 and 1:2 2. The water/cement ratios were those which gave seventy five mm slump without the inclusion of fibres with 0.85 1/50 kg cement of conplast 337. Three beams were cast and tested at twenty eight days with the percentages 4%, 7%, and 10% by weight of the matrix for each mix (an extra 12% for the mortar mix as well).

As already mentioned the fifty mm length fibres were used in this investigation.

6.22 Results and discussion of the workability strength investigation

Since the same mix designs as for the melt extract fibres were used, it was possible to compare their workabilities and strengths in the mixes.

Figures 4.1 to 4.4 (slump and V-B tests of the melt extract fibres) compared with Figures 6.1 to 6.4 (of the fifty mm D-form fibres) show that the latter is more workable than the twenty five mm melt extract fibres. This is due to the lower aspect ratio of the D-form fibres. Figure 6.2 of the mortar mix if plotted with the Figure 3.7 obtained from J. Edgington's Ph.D thesis will give an aspect ratio of around fifty for the fifty mm D-form fibres. The aspect ratio equals length over "diameter" of the fibre. Hence, the equivalent diameter for the fifty mm D-form fibre will be equal

The effect Of Fibres (50mm long- D- Form fibres) content

on slump of O.P.C. + Sand

MIX DESIGN : 1 : 2.4 ; $w/c = 0.3763$

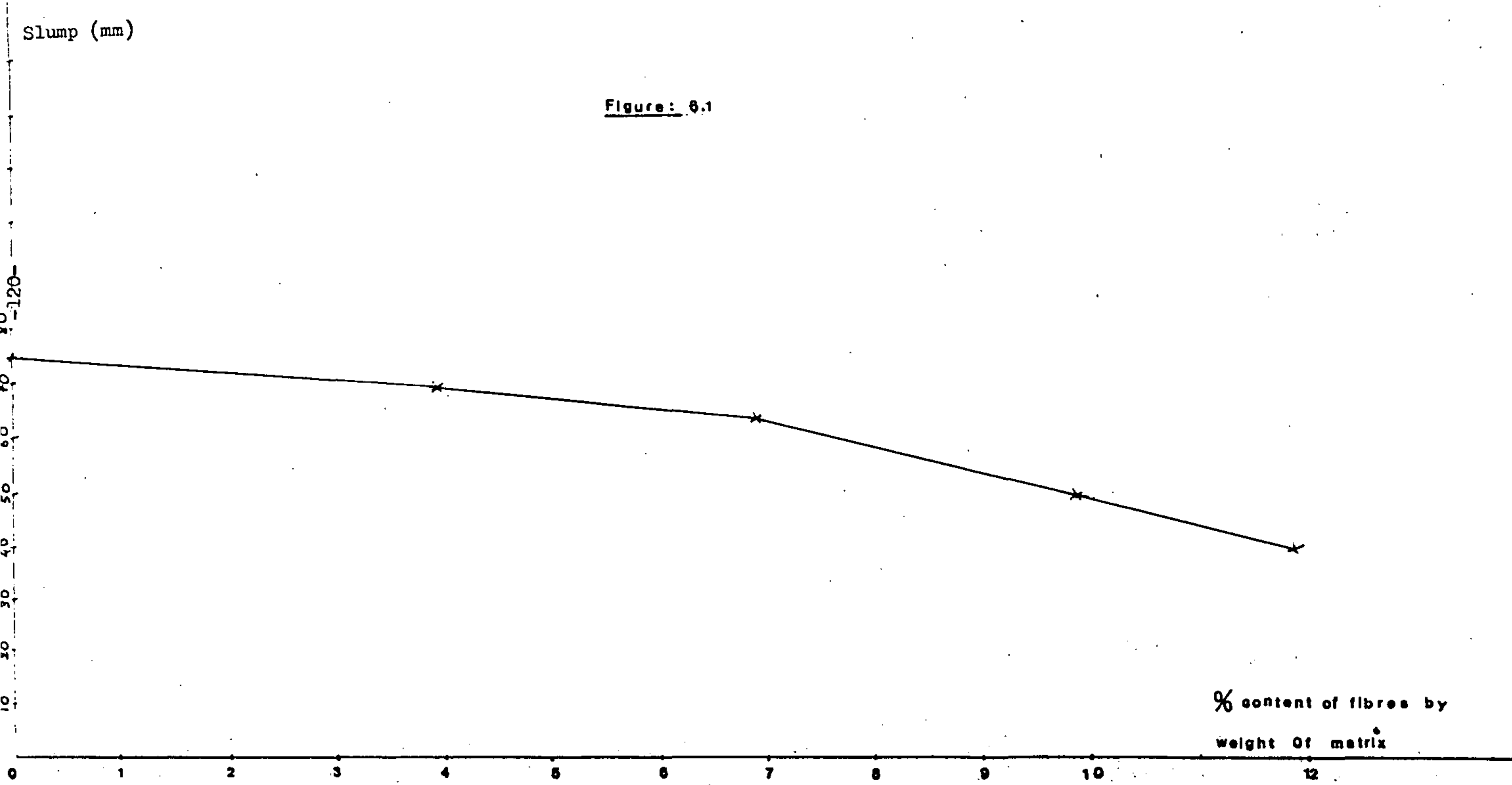


Figure: 6.1

The effect Of Fibres (50mm long- D- Form fibres) content

on V- B time of O.P.C. + Sand

MIX DESIGN : 1 : 2.4 ; W/c = 0.3763

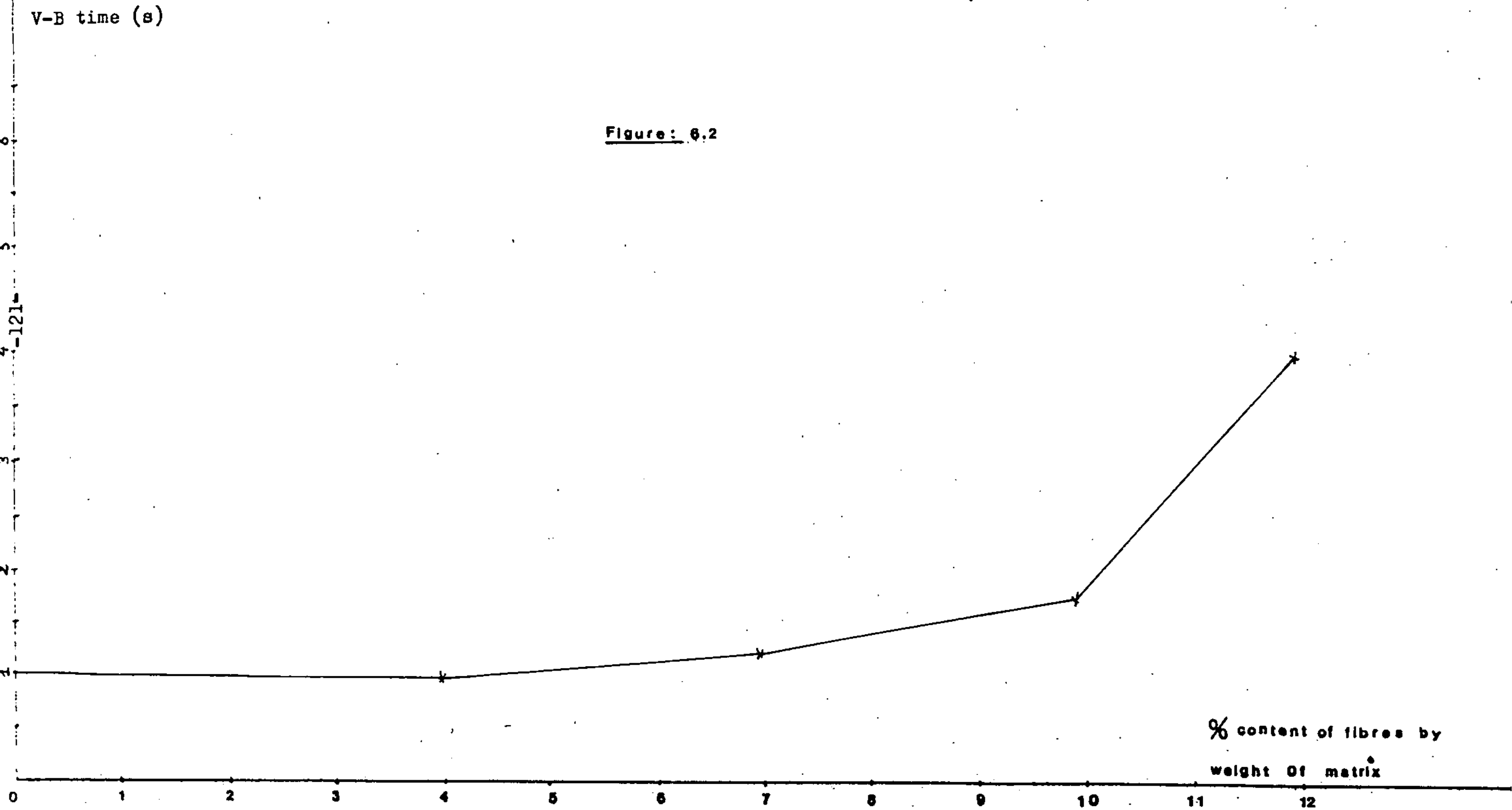


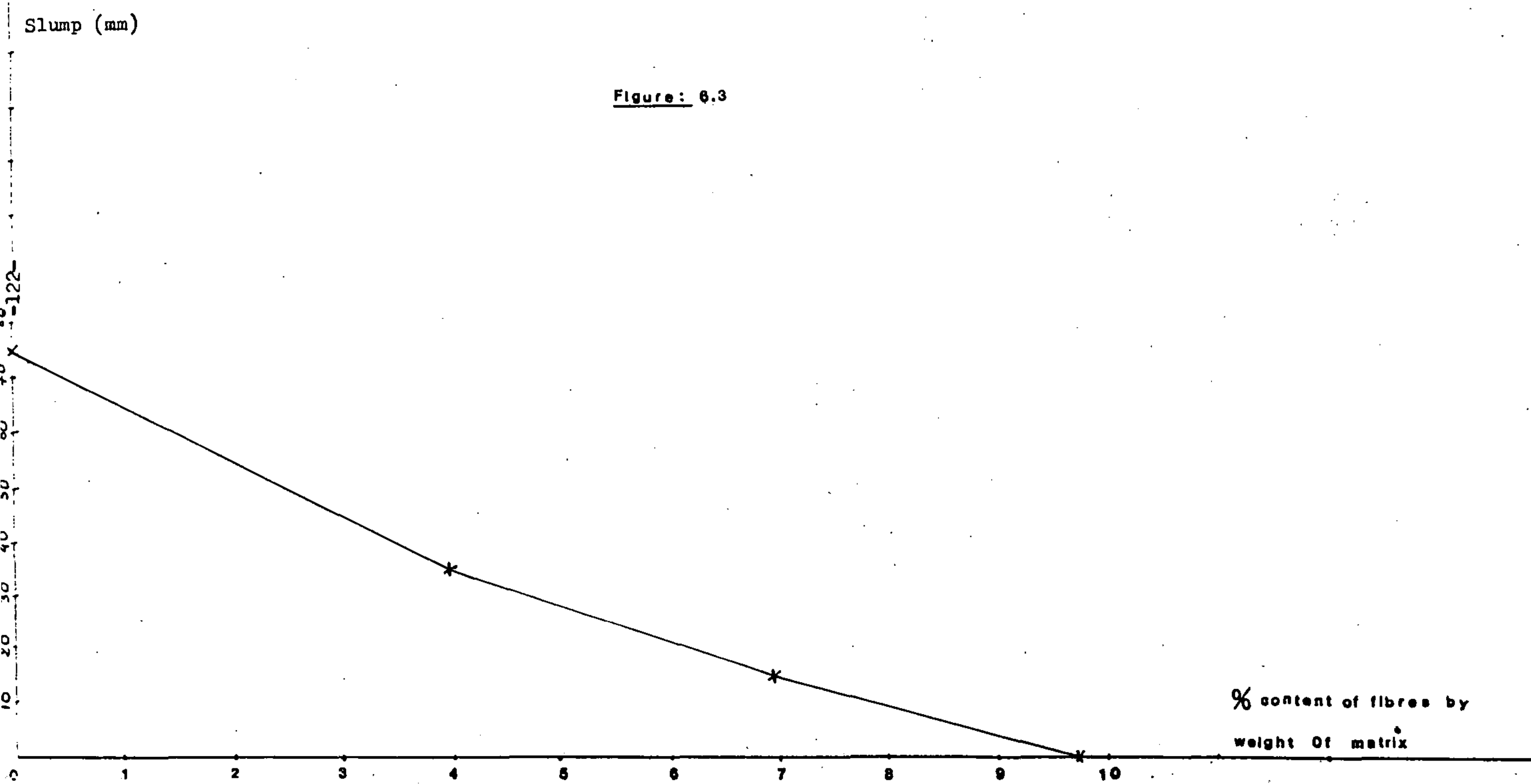
Figure: 6.2

The effect Of Fibres (50mm long D- form fibres) content

on slump of O.P.C. + Sand + 10mm MAX. AGG.

MIX DESIGN : 1 : 2 : 2; $W/_{C}$ = 0.384

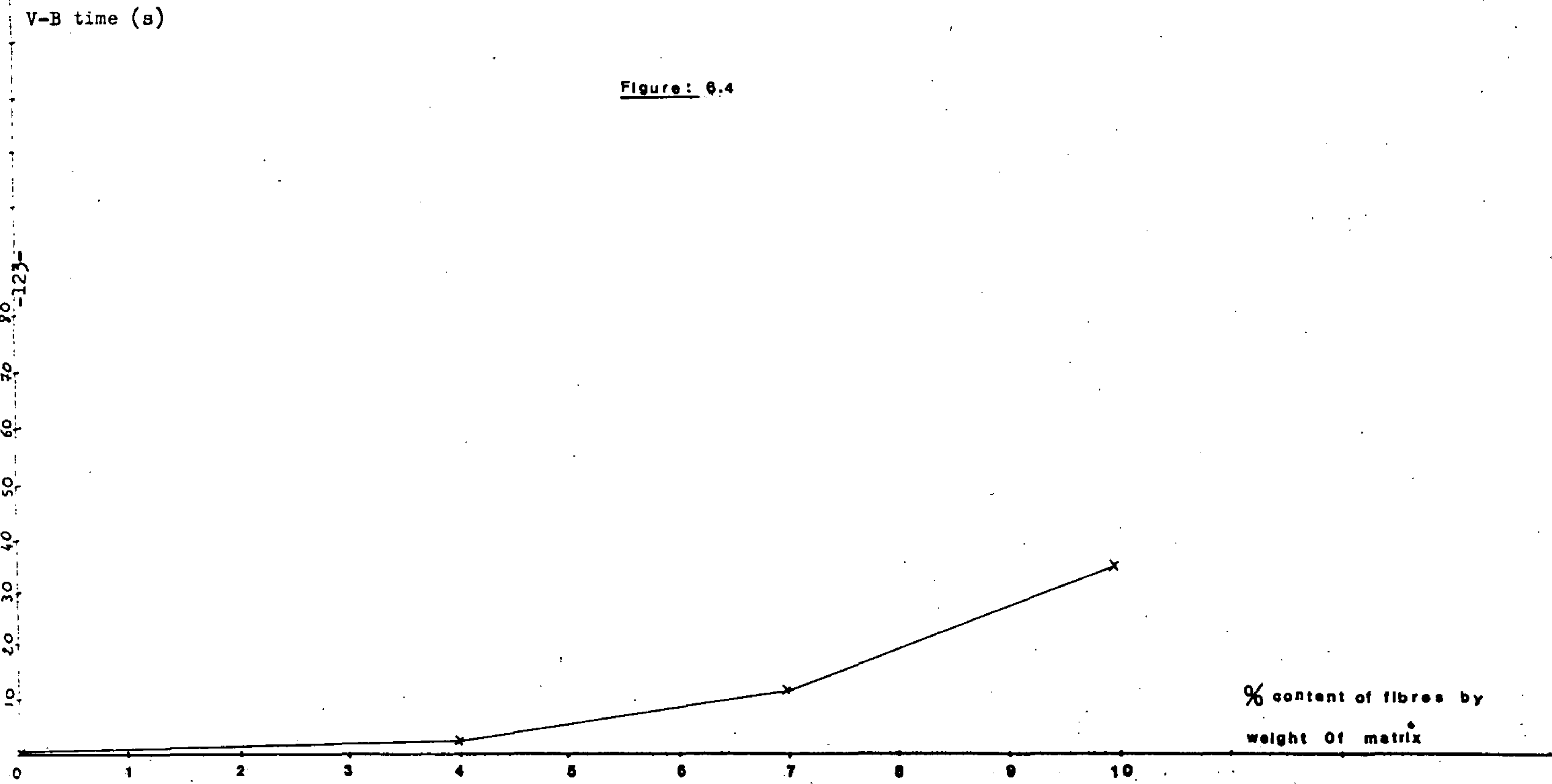
Figure: 6.3



The effect Of Fibres (50mm long- D- Form fibres) content on V-B time of O.P.C. + Sand + 10 mm MAX. AGG.

MIX DESIGN : 1 : 2 : 2 ; w/c = 0.384

Figure: 6.4



to one mm.

As in the strength investigations from Chapter 4, the compressive strengths were not greatly altered by the inclusion of fibres, it was decided to do only the flexural test. The results with the same mixes as for the workability are plotted on Figures 6.5 and 6.6

A simple comparison with Figures 4.25 and 4.27 shows that the fifty mm D-form fibres give higher flexural strengths than the twenty five mm melt extract fibres. This is probably due to their length, their good bonding to matrix and their relatively high cross sectional area. It was noticed that they never broke but pulled out of the matrix. At 10% fibres by weight of the matrix they gave a flexural strength increase of 8% and 20% for the 1:2.4 and 1:2 2 mixes respectively over the twenty five mm melt extract fibres.

6.23 Thin sheet composites

Here also a very limited investigation was carried out using thirty eight mm D-form fibres.

The 166mm × 50mm × 6 mm specimens were taken, prepared and teste in the same way as described in Chapter 5. Due to the relatively little gain in strengths by using the 3:1 mix design instead of the 2:1 mix design (see Chapter 5), it was decided to use the latter mix design with the same water/cement ratio 0.325 as the melt extract fibres.

The tests were carried out at fourteen days after being cured with the smooth face in tension only.

The results were calculated in the same manner as those of the melt extract fibres (see Table 6.1).

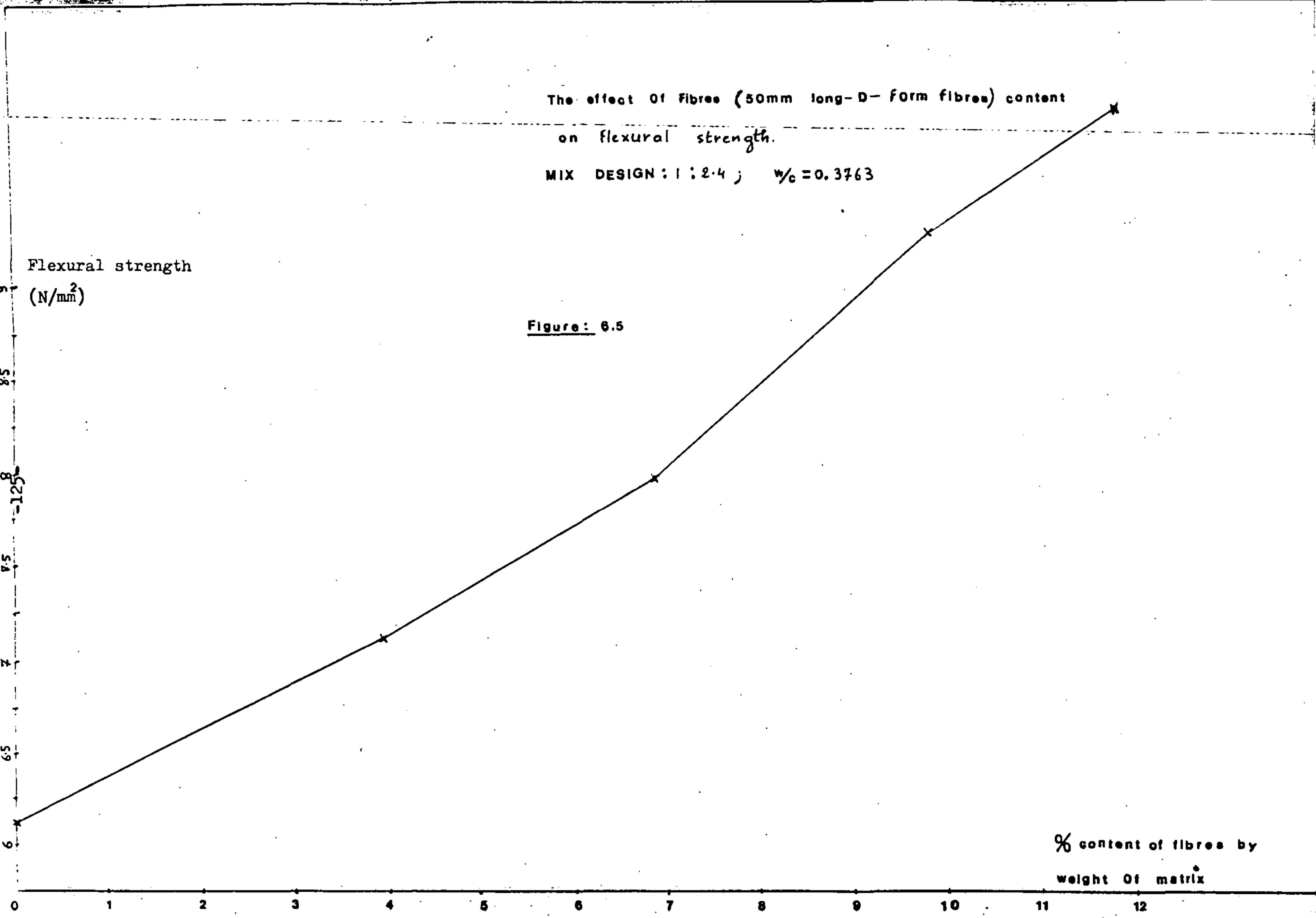

The effect Of Fibres (50mm long-D- Form fibres) content
on flexural strength.
MIX DESIGN : 1 : 2·4 ; w/c = 0.3763
Flexural strength
(N/mm²)
% content of fibres by
weight Of matrix
0
1
2
3
4
5
6
7
8
9
10
11
12
6
6.5
7
7.5
8
8.5
9

Figure: 6.5

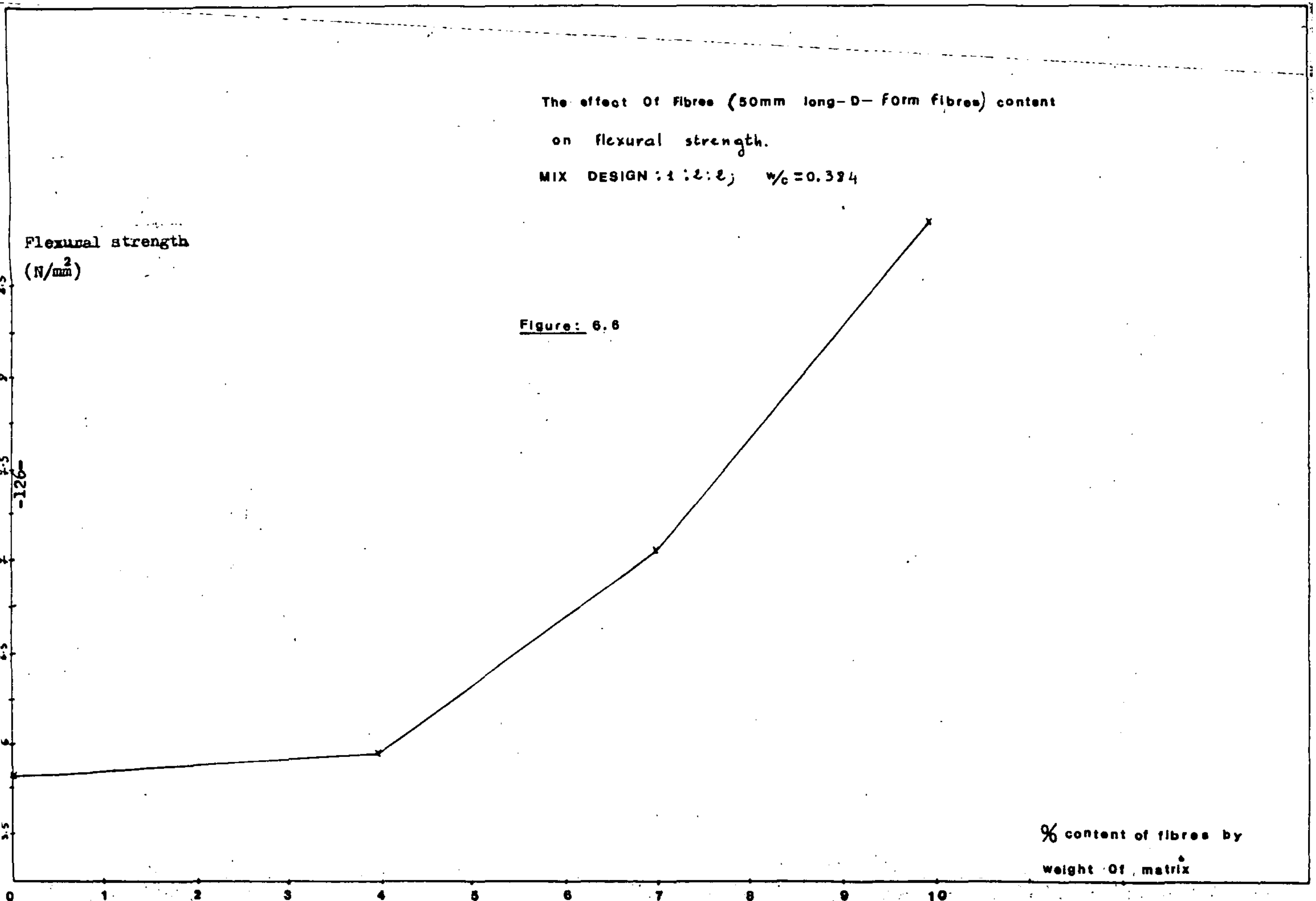

The effect Of Fibres (50mm long- D- Form fibres) content
on flexural strength.
MIX DESIGN : 1 : 2 : 2 ; w/c = 0.394
Flexural strength
(N/mm2)
% content of fibres by
weight Of matrix
0
1
2
3
4
5
6
7
8
9
10

Figure: 6.6

Table 6.1 Flexural results of 38mm D-form fibres in thin sheets.

BEAM TYPE *	Modulus of rupture mean value 90% (N/mm^2)	Limit of proportionality mean value 90% (N/mm^2)	Youngs modulus mean value 90% (N/mm^2)	Toughness index mean value 90% by Max load criterion	0.8 Max load criterion
6/12	9.3 3.2	8.7 2.7	18735.2 10052.7	1.56 0.6	3.75 1.3
6/14	10.7 2.1	9.4 1.9	19837.2 11354.8	1.98 0.5	4.53 1.2

* Thickness beam (mm)/ % fibre by weight of matrix.

The toughness indexes and the Youngs modulus are roughly the same as in the melt extract fibres but the modulus of rupture and the limit of proportionality are both [illegible] 30% less than those of melt fibres.

Then in conclusion the twenty five mm melt extract fibres give stronger thin composite sheets than the thirty eight mm D-form fibres. This might be due to the fact that they travel less during compaction towards the smooth rather than melt ones because of their higher surface area. Being relatively big they are not densely dispersed in the specimins as are the melt fibres.

SECTION THREE D-form steel fibres for crack control and the comparison of their results with the melt extract fibres

CHAPTER SEVEN : D-FORM STEEL FIBRES FOR CRACK CONTROL IN REINFORCED BEAMS

Cracking in concrete members, whether caused by self imposed strains due to restrained shrinkage, thermal movements or due to external loading is one of the major problems in the construction of concrete structures. For serviceability it is necessary to control the crack width produced by working loads. CP 110[19] gives a maximum crack width of 0.3mm for design of concrete members not exposed to hostile environments. The design of concrete members is governed by deflections and crack size and thus full exploitation of the structural strength of the members is not possible. In this investigation the 25mm long D-form steel fibres were used to control the flexural cracking and a comparison was possible with the use of the 25mm- grade 410 melt extract steel fibres. These fibres were used by another student[30] in the Civil Engineering Department. The scope of the investigation was as follows:

i) To investigate the effect of D-form fibre boards on the tensile faces of normally reinforced beams in flexure ;

ii) To investigate the effect of fibre concentrations and board thicknesses;

iii) To compare results obtained with similar work on the 25mm- grade 410- melt extract steel fibres.

7.1 Type of fibres used in the tests

The fibres used in this investigation were very new. For their appearance and how they were obtained see Chapter six.

7.2 Theories of cracking

Since the fibre reinforced layers are relatively thin in comparison with the height of the beams, they can be assumed to be in tension when the beams are tested in flexure. The theories of cracking will then be studied in tension.

7.21 Cracking due to tension

By considering the concrete stress at a distance from a crack face and the accompanying steel stresses (see Figure 7.1), the uniform concrete stress theory[31] shows that the tensile stress

$$F'_t = \frac{\pi D}{A_c} \int_0^{L/2} u_x \, dx \qquad (7.1)$$

where A_c = cross sectional area of concrete

D = diameter of the steel bar

L = minimum distance between cracks

u = bond stress at a distance x

If $\frac{x}{L} = \phi$ and f is a function of ϕ, from equation 7.1 we can deduce that:

$$L = \frac{F'_t}{u_m} \frac{A_c}{\pi D} \cdot \frac{1}{\int_0^{1/2} f(\phi) d\phi} \qquad (7.2)$$

The distance between the cracks will be variable, but it is expected in general to be near L. If the distance between two primary cracks is L, the secondary cracks will form at a distance $\frac{L}{2}$. However if the distance is less than L and greater than $\frac{L}{2}$ the spacing of the new crack will appear between L and $\frac{L}{2}$. The average crack width

$$w = 2\int_0^{L/2} S_x \, dx \quad \text{where}$$

$$S_x = \frac{f_{sx}}{E_s} - \frac{f_{tx}}{E_c}$$

f_{sx} = steel stress at a distance x from a crack face

f_{tx} = concrete stress at a distance x from a crack face

E_s = Youngs modulus for steel

E_c = Youngs modulus for concrete

Broms[31] stated that a concrete section subjected to direct tension will develop areas of high stress within a circle of diameter proportional to the ratio of the distance between the crack faces or ends.

He suggested a spacing of cracks between c and 2c with an average of 1.5c, where c is the concrete cover over the steel.

7.3 Approaches to crack control

The introduction of fibre boards is by no means to stop the formation of cracks, which would be impossible, but is to improve the ability of concrete to take more stress at which cracks would start, to reduce the width of the largest crack, and to reduce the sizes of the large cracks by having more smaller cracks.

The use of fibres can isolate the flows and prevent propagation, and it also increases the energy required to drive a crack forward in the concrete.

7.4 Major variables in crack formation

Broms uses the steel strain as his major parameter. He found the strains he used beyond the proportional limit to be more accurate. Gergerly[33] and Hognestad[34] suggested the average area of concrete surrounding each reinforcing bar as a major variable. The area is defined as the total area of concrete having the same centroid as the steel divided by the number of bars (see Figure 7.2).

Kaar[35] and Mattock[36] suggested the maximum crack width as

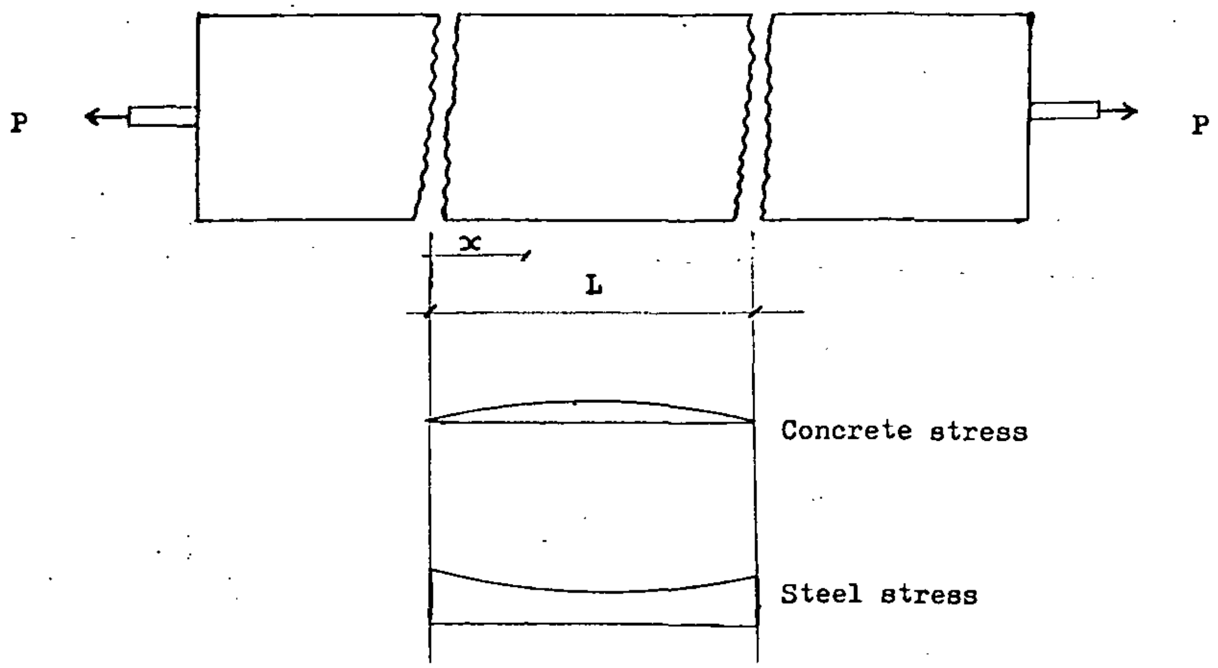


Figure:7.1 Uniform concrete stress theory.

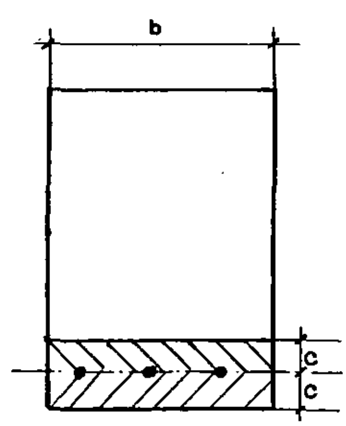


Figure:7.2 Average area of concrete surrounding each bar

$$W_c \max = 0.115 \sqrt[4]{A} f_s \times 10^{-6}$$

where A = average area of concrete around each bar (in^2) and

f_s = reinforcing stress (p.s.i.)

7.5 Geometry of D-form fibres

The fibres as said before have a D-form cross sectional shape. They are crimped fibres (see Figure 7.3).

It was expected that their crimped shape would give good bonding characteristics. Their D-form cross section allowed more surface area which had an effect on the crack patterns. Krenchel[37] has shown that the greater the specific surface area of fibres in a mix the closer the cracks are together and the smaller their widths.

7.6 Use of fibre boards (see Figure 7.4)

It was expected that the use of fibre boards could control cracking to acceptable limits and transform the brittle behaviour of concrete to ductile behaviour.

7.7 Laboratory tests and equipment

To gain the most efficient use of the fibres they were dispersed only in the mortar boards moulded on the bottom face of the beams. The maximum thickness of the boards is twelve mm, whereas the fibres are twenty five mm long; this allows the fibres to be distributed in a plane perpendicular to the crack propagation.

7.71 Variables in the tests.

Six, eight, ten and twelve fibre percentages by weight of the matrix were introduced in the two boards of eight and twelve mm thickness. These percentages were chosen because earlier work showed that there was little advantage to be gained by using less than six per cent. It was possible to use them due to the good workability of

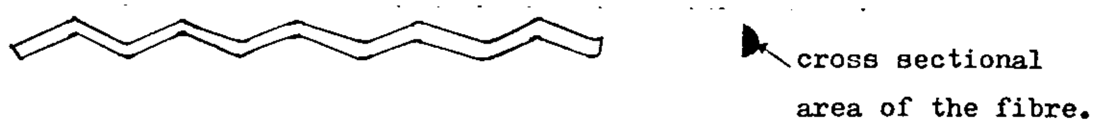


Figure:7.3 D-form fibre shape (not to scale).

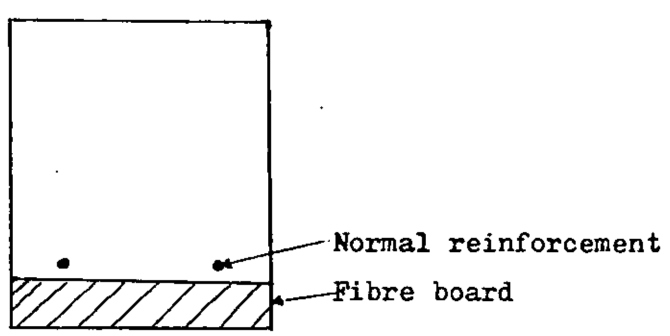


Figure:7.4 Fibre board used as crack control.

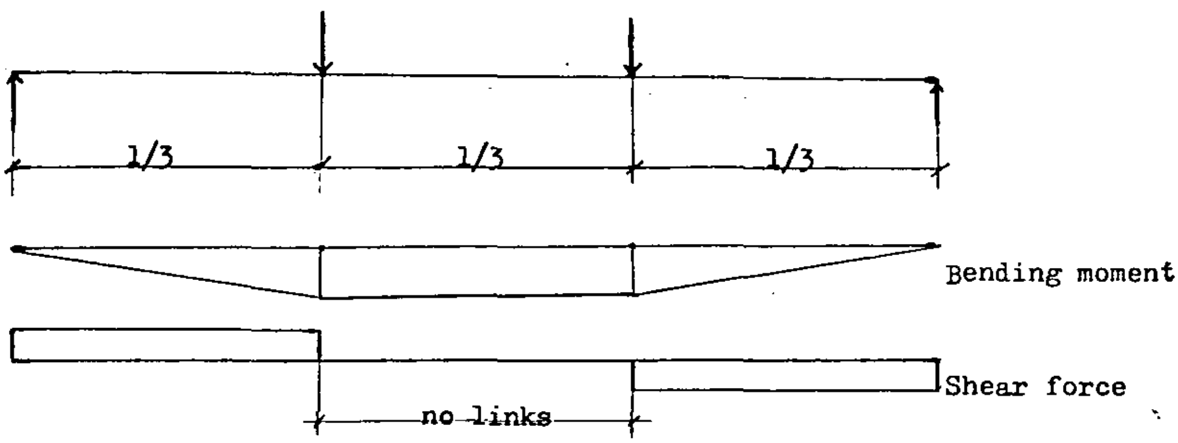


Figure:7.5 Load arrangement for the tests.

the D- form fibres (see Chapter Six). For comparison a beam without fibres was also tested.

7.72 Beam design (see Figure 7.6)

For the purpose of comparison, the dimensions of the beams tested were the same as the ones tested by D.P.Denness.[30] They were designed to have an under-reinforced failure and shear reinforcement was added.

i) Reinforcement calculations;

The tensile steel bars were calculated using the rectangular parabolic stress block C.P.110 and were calculated to give an ultimate moment of about eight kNm. The reinforcement was kept low to ensure a ductile under-reinforced failure to have large deflections and cracks.

Shear reinforcement was included in the shear zones to prevent a rapid shear failure.

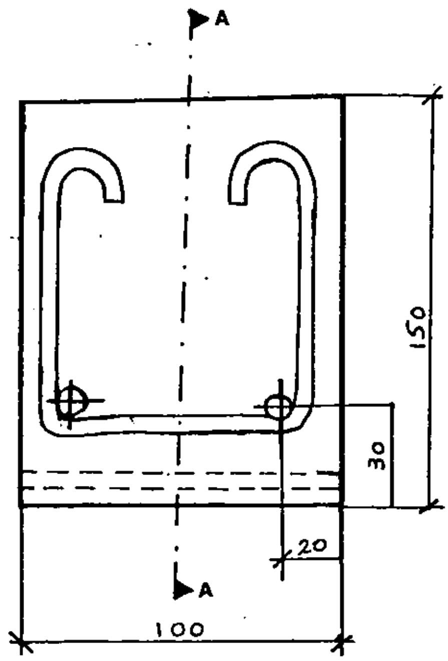
The cracks measured during the tests were all in the pure bending region (which has no shear links);

ii) Concrete mix design;

The 1:2:2 mix B (see Table Two of Chapter Three) was chosen for the beams with the water/cement ratio 0.468 (75mm slump). The strength of the mix was only 30 N/mm^2 at fourteen days after stripping the moulds which ensures that the steel yields before the concrete crushes.

7.73 Design of fibre reinforced boards

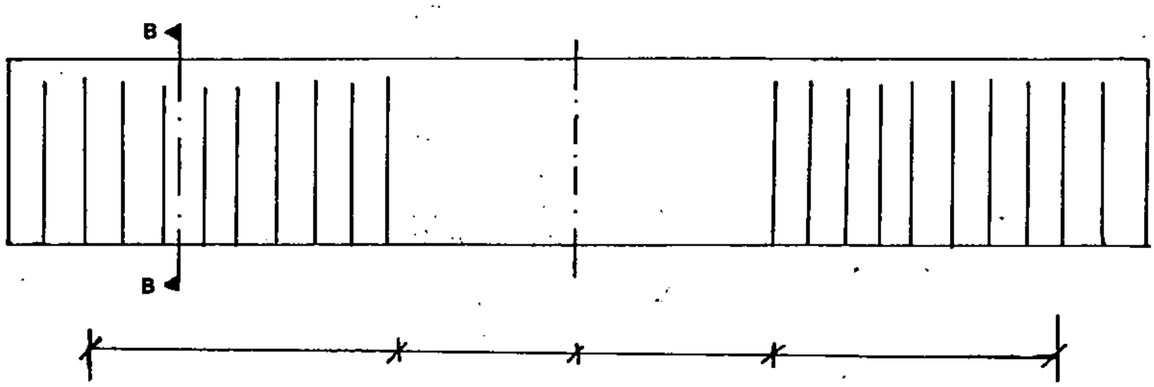
The boards used ran the complete length of the beam. They were cast first in the mould of the beams and left for four hours to dry



SECTION B-B

(N . T . S .)

Links @ 80 mm C/C



SECTION B-B

(N . T . S .)

Figure 7.6 Detail of the test beam

before casting the beams on top of them in order to ensure a monolithic composition.

i) Mix used for boards;

The mortar mix used was the 1:2:4 mix A (see Table Two of Chapter Three). The water/cement ratio was 0.376 with 0.85 l of conplast 337/50 kg of cement.

7.74 Laboratory procedure for making beams

The beams were allowed to cure for twenty four hours in the moulds under polythene sheets. After being stripped they were painted with a curing compound because they would not fit into the curing tank. In order to see the cracks easily the beams were whitewashed.

7.75 Test loading arrangement

The loading was arranged to be at 1/3 spans as shown in Figure 7.7.

The loads were applied via rollers and semi-circular bearings in order to ensure simple supports with no angular fixity. Steel bearing plates were fixed with plaster to the beams at the loading points in order to prevent localised cracking of the concrete under the loads and to even out small undulations in the concrete surface so that the load is evenly applied.

i) Test rig used (see Figure 7.8 and plate 7)

The maximum load that the rig can apply is five tons. Using the gearing mechanism, the rate of loading was regulated at four mm/min which gave a constant variation of the central deflection per unit of time for each beam. The central deflections and loads were read by using the curves given by a plotter. Deflections were only read

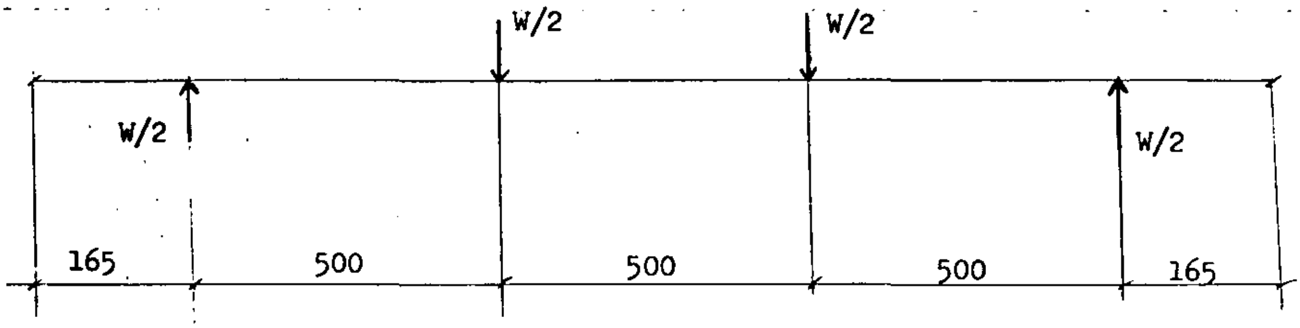


Figure:7.7 Load positions on the beam.

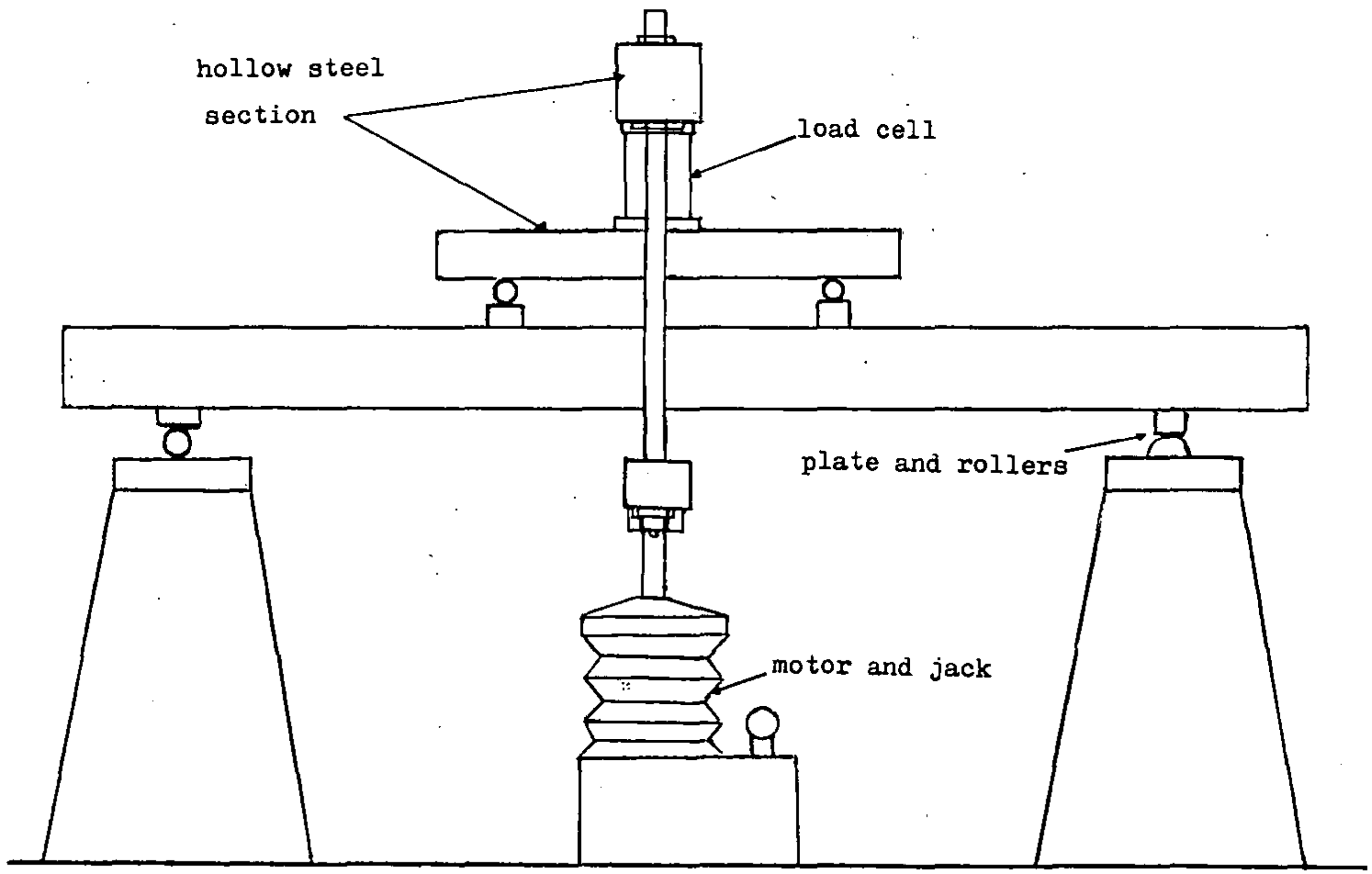


Figure:7.8 Test rig used for the crack control tests.

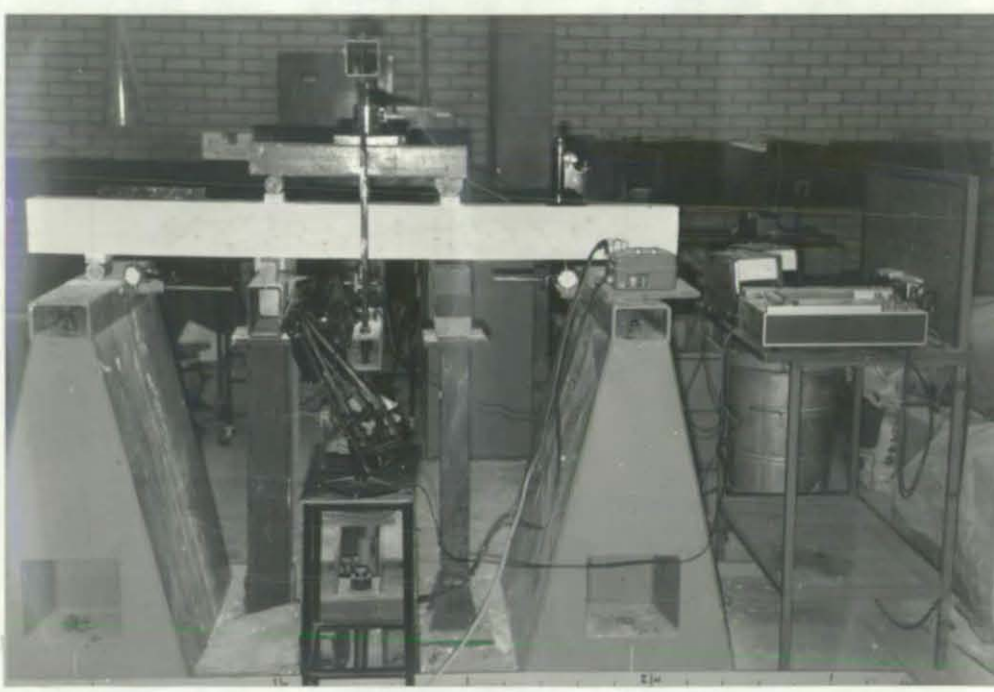


Plate:7 Test rig used for the crack control to check that the beams behaved similarly to one another and I did consider it necessary to mount gauges to measure the compression at the plaster supports which I then used to deduct their averages from the central deflections in order to plot the deflection load of Figure 7.9.

7.76 Measurement of crack widths

The crack widths were measured by using a microscope. Each division of its scale after calibration was found to be 0.0114mm. Crack widths were measured at the bottom of the beams where they are generally the widest. In certain cases I had to measure them where their widths were at a maximum and not at the bottom.

7.8 Testing procedure

At the beginning small loads were applied until the appearance of the first crack, after which a load of around five kN was added each time. After each load addition:

i) The maximum width of each crack was measured;

ii) The load and central deflection were recorded on the plotter;

iii) The compressions of the support plasters were measured;

iv) The length of each crack was measured;

v) The cracks were numbered in order of their appearance and their number recorded;

vi) The loads were marked on the upper extremity of the cracks they caused.The last loads were the loads after which the beams failed.

7.9 Results and discussion

The beams were tested fourteen days after stripping the moulds. The results of the test measurements are given in Appendix Four.

The beams were numbered as follows:

Beam 1 : 0% fibre

Beam 2 : 6% fibre 8mm board

Beam 3 : 8% fibre 8mm board

Beam 4 : 10% fibre 8mm board

Beam 5 : 12% fibre 8mm board

Beam 6 : 6% fibre 12mm board

Beam 7 : 8% fibre 12mm board

Beam 8 : 10% fibre 12mm board

Beam 9 : 12% fibre 12mm board

All the beams, as experienced by D.P.Denness, failed in an under-reinforced ductile manner and Figure 7.9 (load deflection) shows that the curve of each beam can be divided in the three known behaviours of concrete in flexure:

i) O-A Elastic behaviour before the first crack occured at point A (first crack load);

ii) A-B Elastic behaviour with appearance of other cracks;

iii) B-C inelastic behaviour to failure. Occurence of more cracks and an increase in their widths.

7.91 Crack propagation patterns

Figure 7.10 shows the cracks on the beams and their positions. The first cracks to appear were primary cracks followed by the occurence of cracks between them known as secondary cracks. There were no cracks developing along the interface of fibre layer and the rest of the beam as witnessed by D.P.Denness and this was due to the good monolithism obtained by allowing the boards to dry only four hours before the concrete of the beams was poured on top of

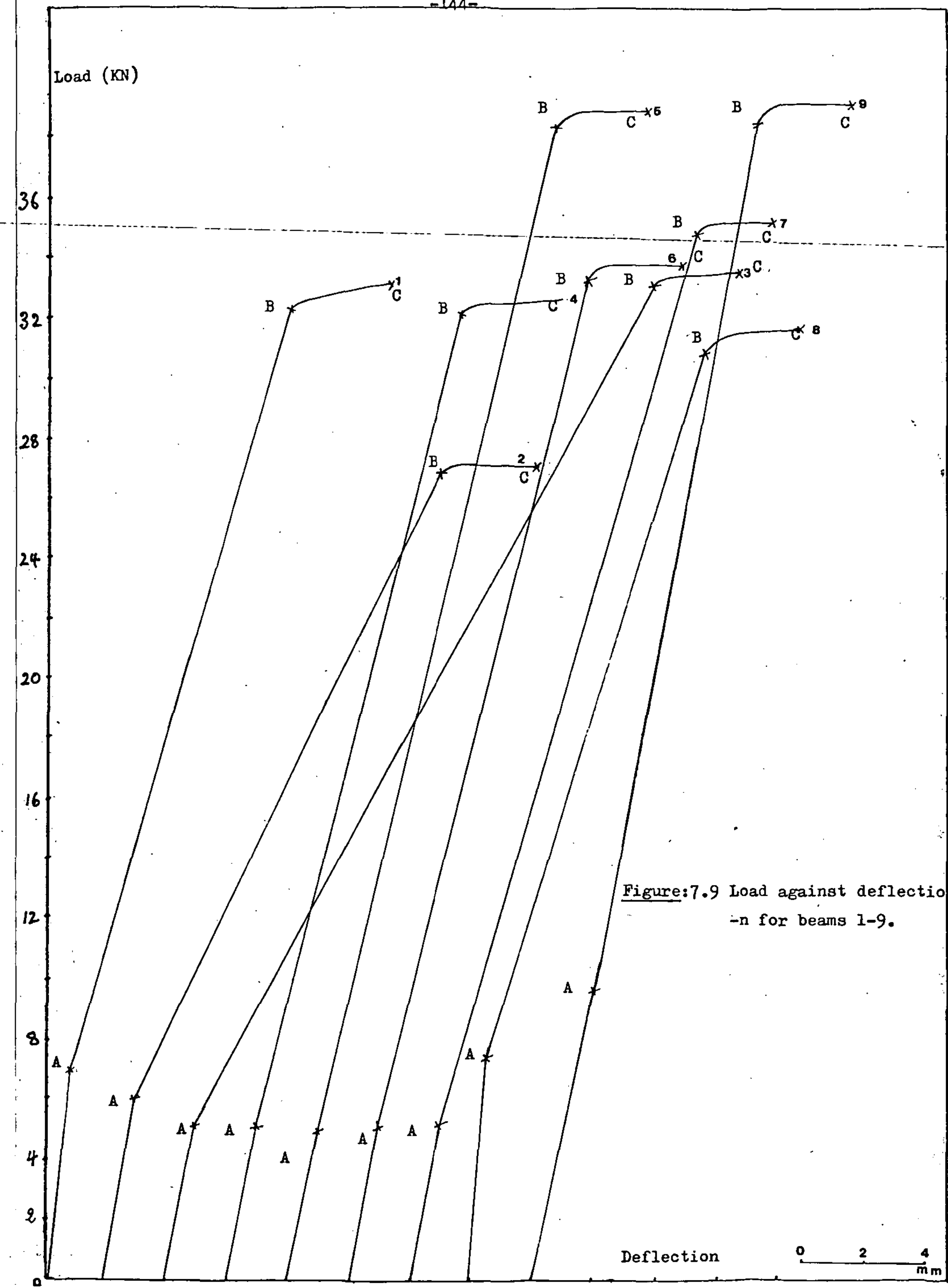


Figure:7.9 Load against deflectio -n for beams 1-9.

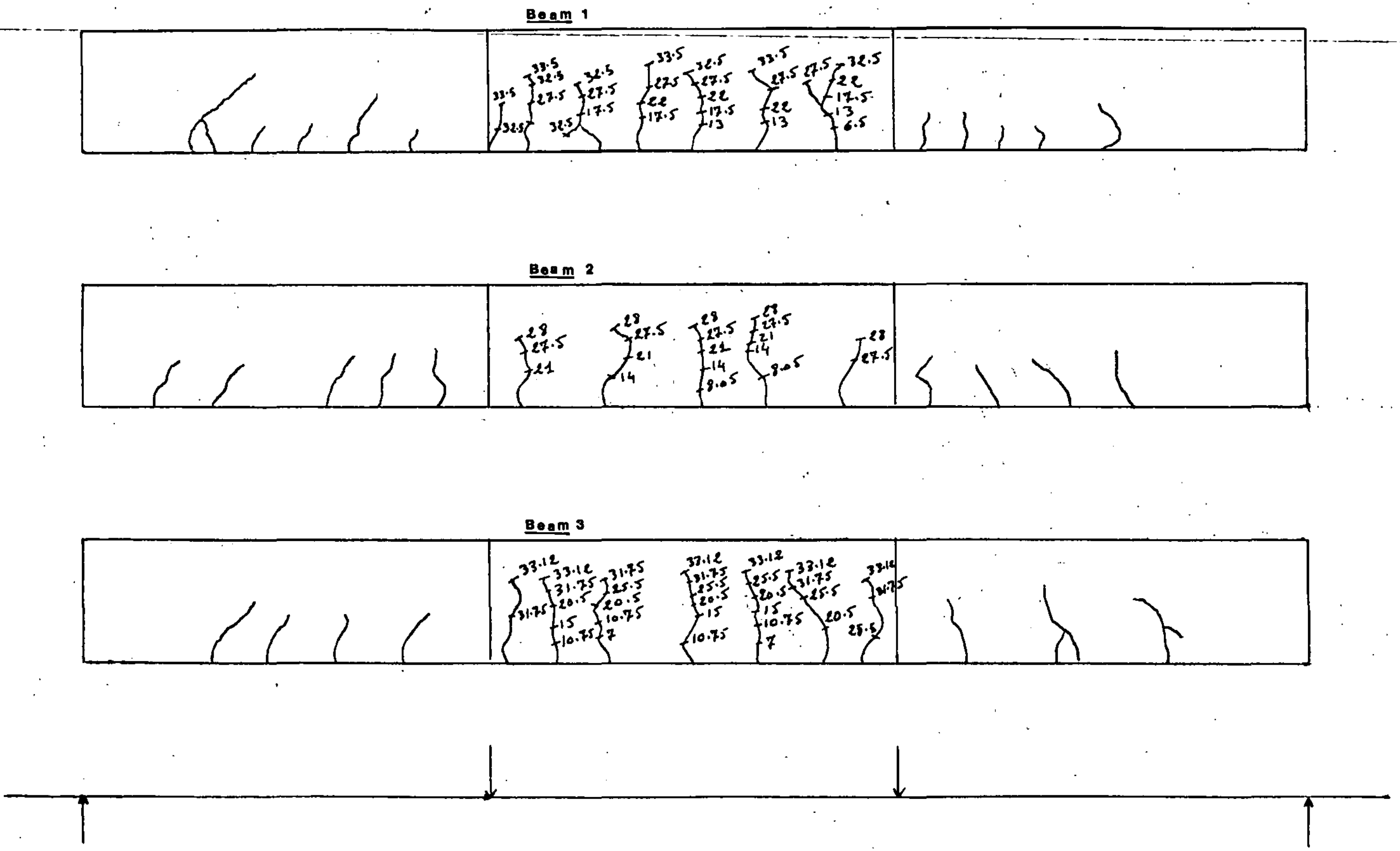


Figure: 7.10 (a) Crack propagation

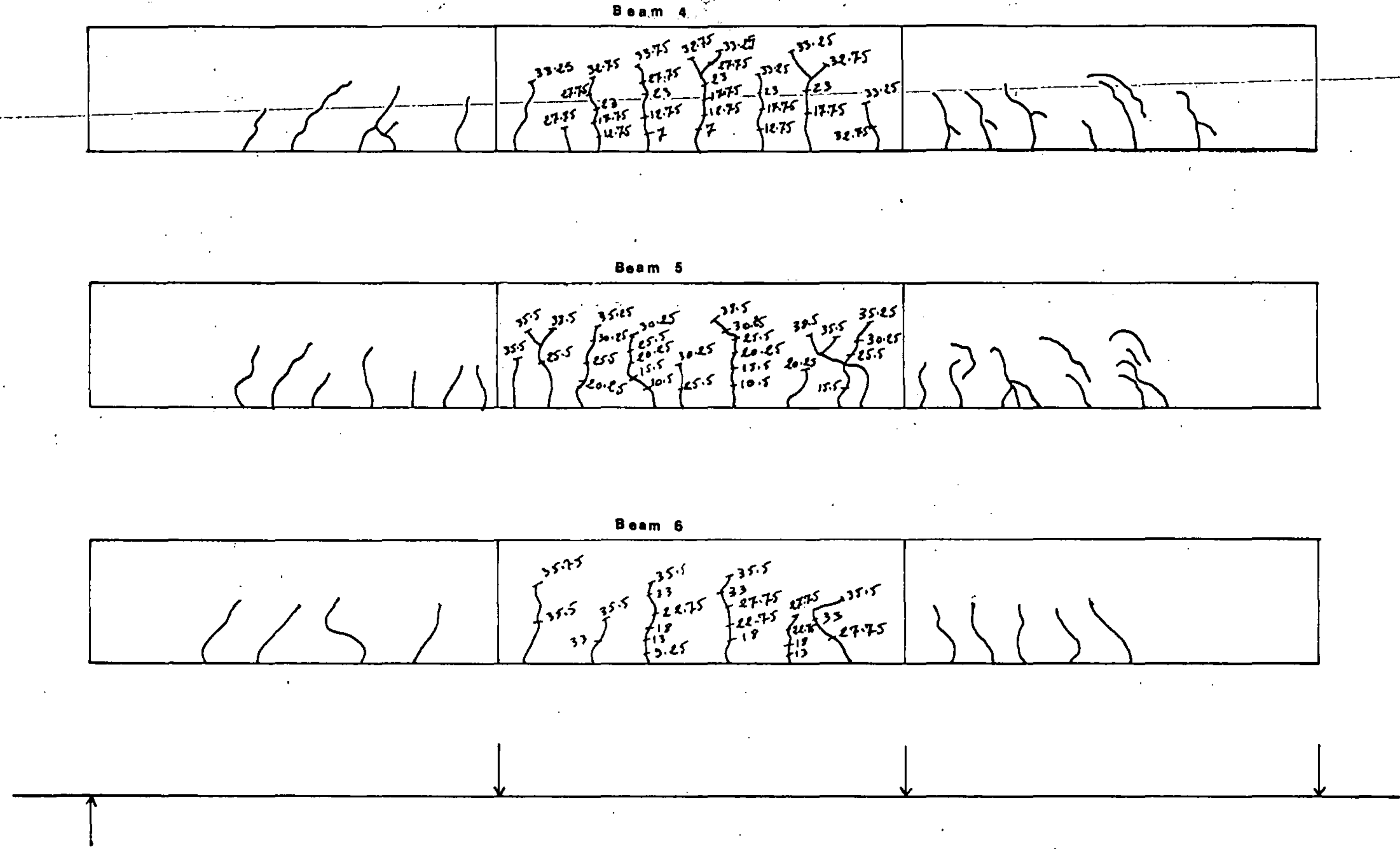


Figure: 7.10(b)

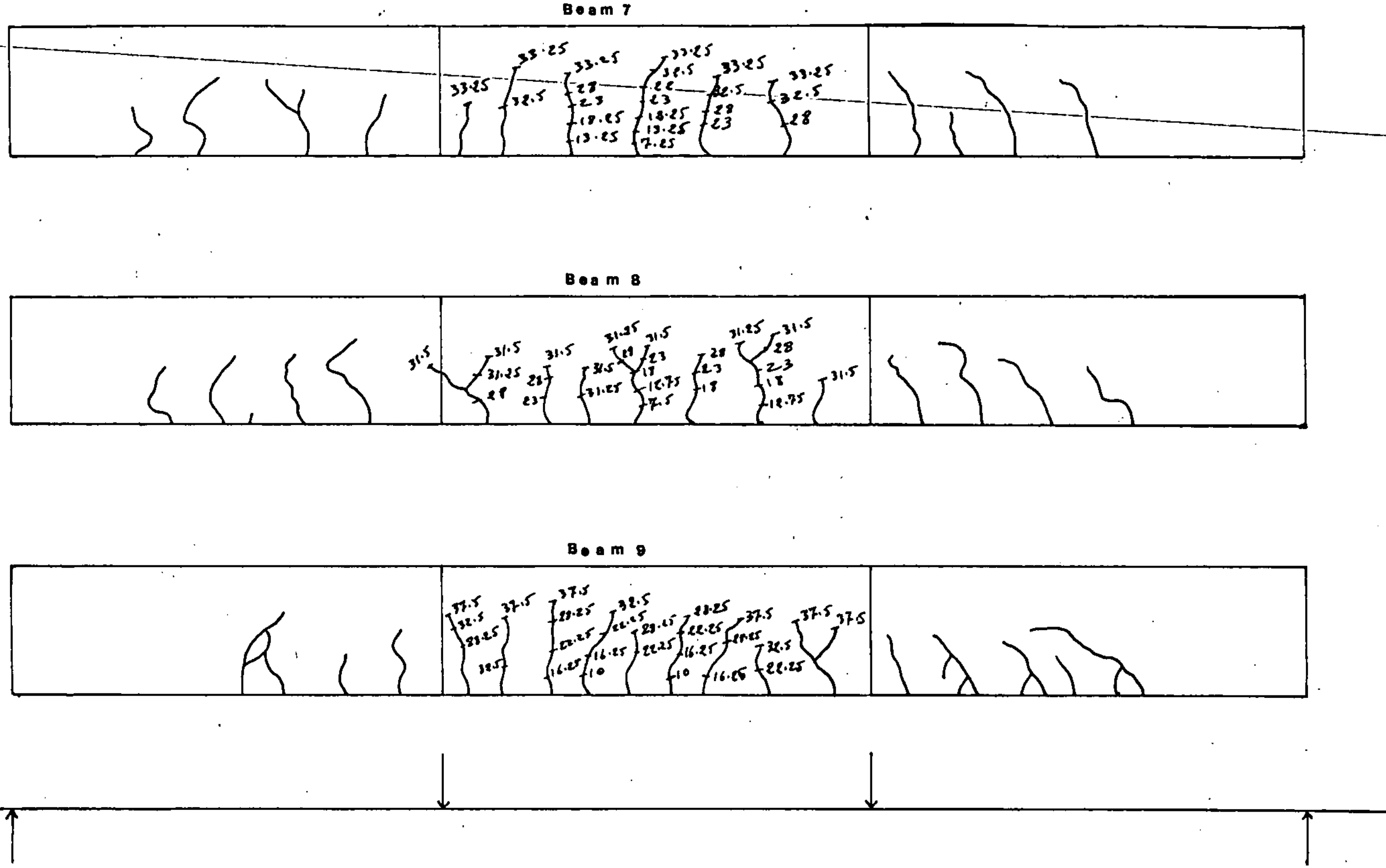


Figure:7.10 (c)

them.

In order to draw a comparison between the use of the twenty five mm melt extract steel fibres and the twenty five mm D-form fibres the growth of the widest crack (which is in practice of great importance) will be plotted against a load ratio as done by D.P.Denness (Figure7.11 and 7.12). The load ratio was defined as the load being applied divided by the failure load of the beam. By doing so, the effects on cracking of concrete strength variations will be reduced.

The D-form fibres showed improvements as crack controls for all the different percentages of fibres used except the 12% fibres in the eight mm board after roughly 50% of the failure load was reached. This could be due to the fact that the 12%fibres in eight mm board is too high for this thickness to be evenly distributed and compacted.

For both the eight and twelve mm boards it was noted (see Figures7.11 and 7.12) that maximum crack widths were least with 10% fibres

In the eight mm board, beam 2 (6% fibres) shows no improvements in controlling the crack over beam 1 which is a control beam. Beam 3 (8% fibres) and beam 4 (10% fibre) show a clear improvement.

All the beams with twelve mm boards show improvements over beam 1 and their results are closer to each other than the eight mm

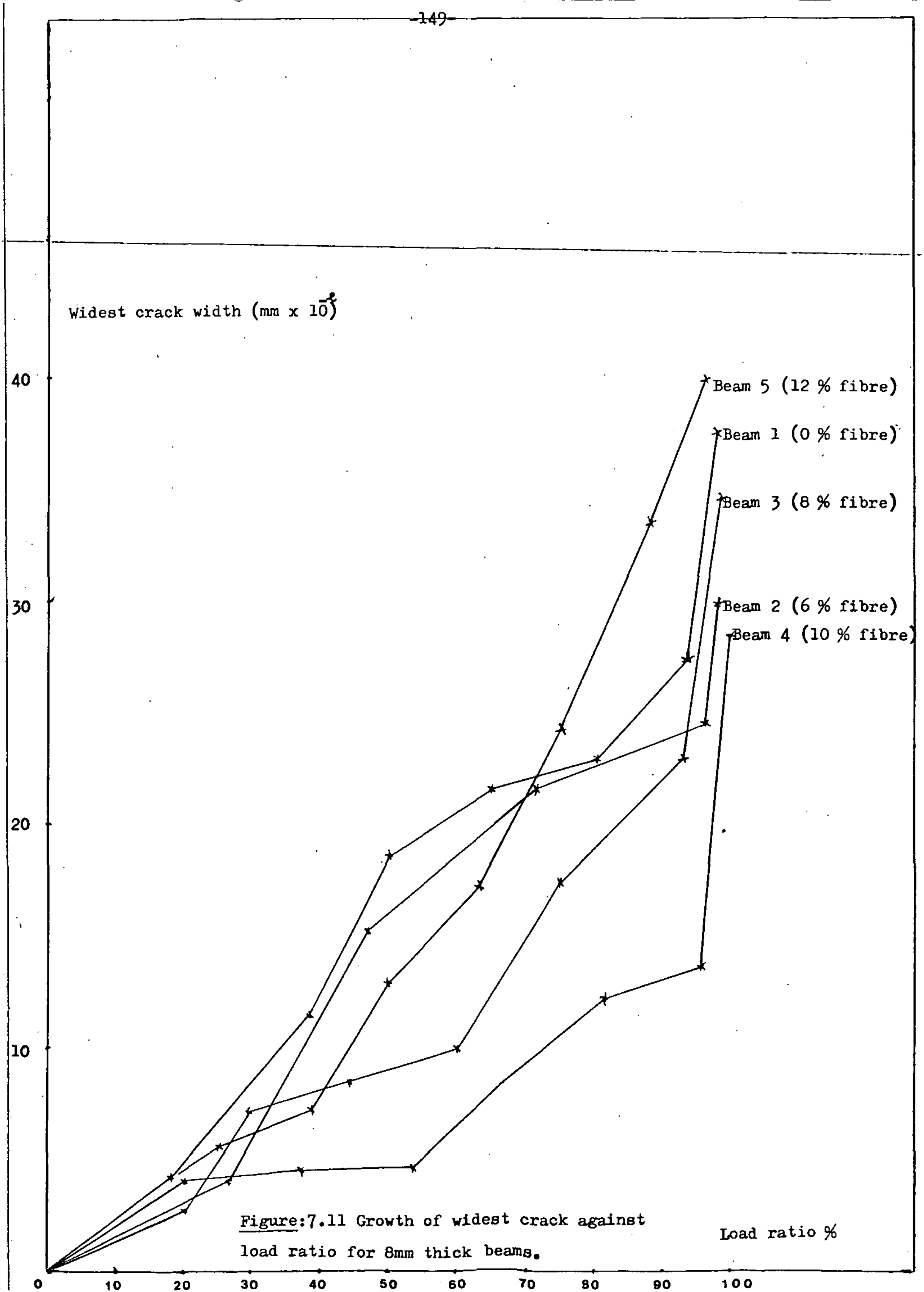


Figure:7.11 Growth of widest crack against load ratio for 8mm thick beams.

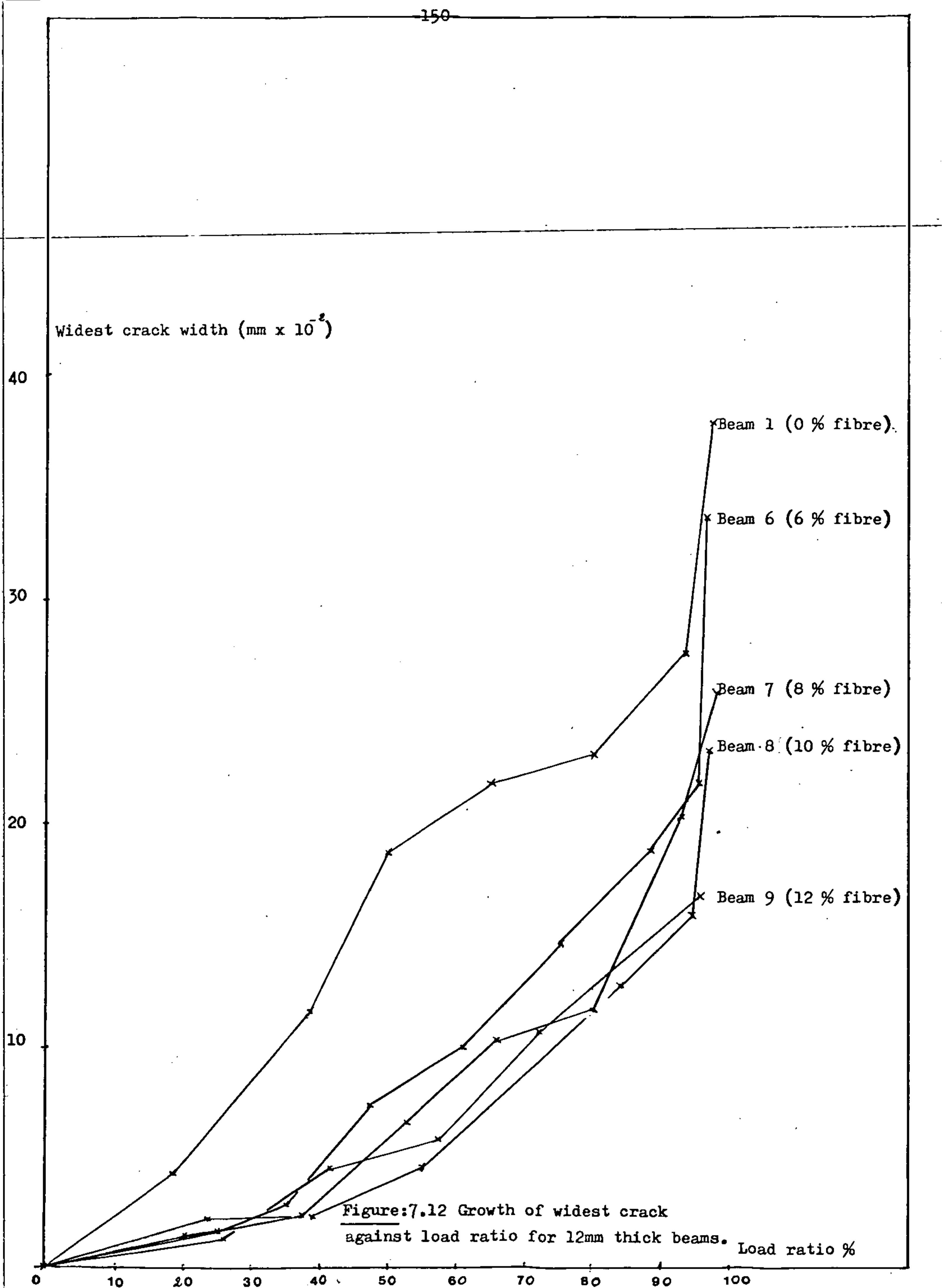


Figure:7.12 Growth of widest crack against load ratio for 12mm thick beams.

board beams.

The D-form fibre eight mm and twelve mm boards gave similar results as crack controllers.However , if we take into account the price of the fibres and the matrix , the 10 % fibres eight mm board must be the best board to use.

In order to compare the results with the twenty five mm melt steel fibres ,the results of the optimum fibre percentages for controlling cracks were drawn on Figure 7.13 from D.P.Denness's results with results of beam 4 and beam 8 of Figures 7.11 and 7.12. It shows that for the same load ratios the cracks are significantly smaller in the case of theD-formfibres than in the case of the melt fibres. This results shows that the D-form fibres are better crack arrestors than the melt fibres. This may be due to their crimped form and the larger surface area.

As it was expected the inclusion of fibres increased the number of cracks which led to a decrease in maximum crack widths at different loads. This also led to a decrease in average crack spacing.

It is difficult to see whether or not the crack lengths (Figure 7.10) have been affected by the inclusion of fibre boards.This is of less importance than the maximum crack widths.

7.10 Conclusion

The presence of high D-form fibre percentages in thin boards at the tensile sides of the beams can have the following effects:

i) Reduce the maximum crack widths;

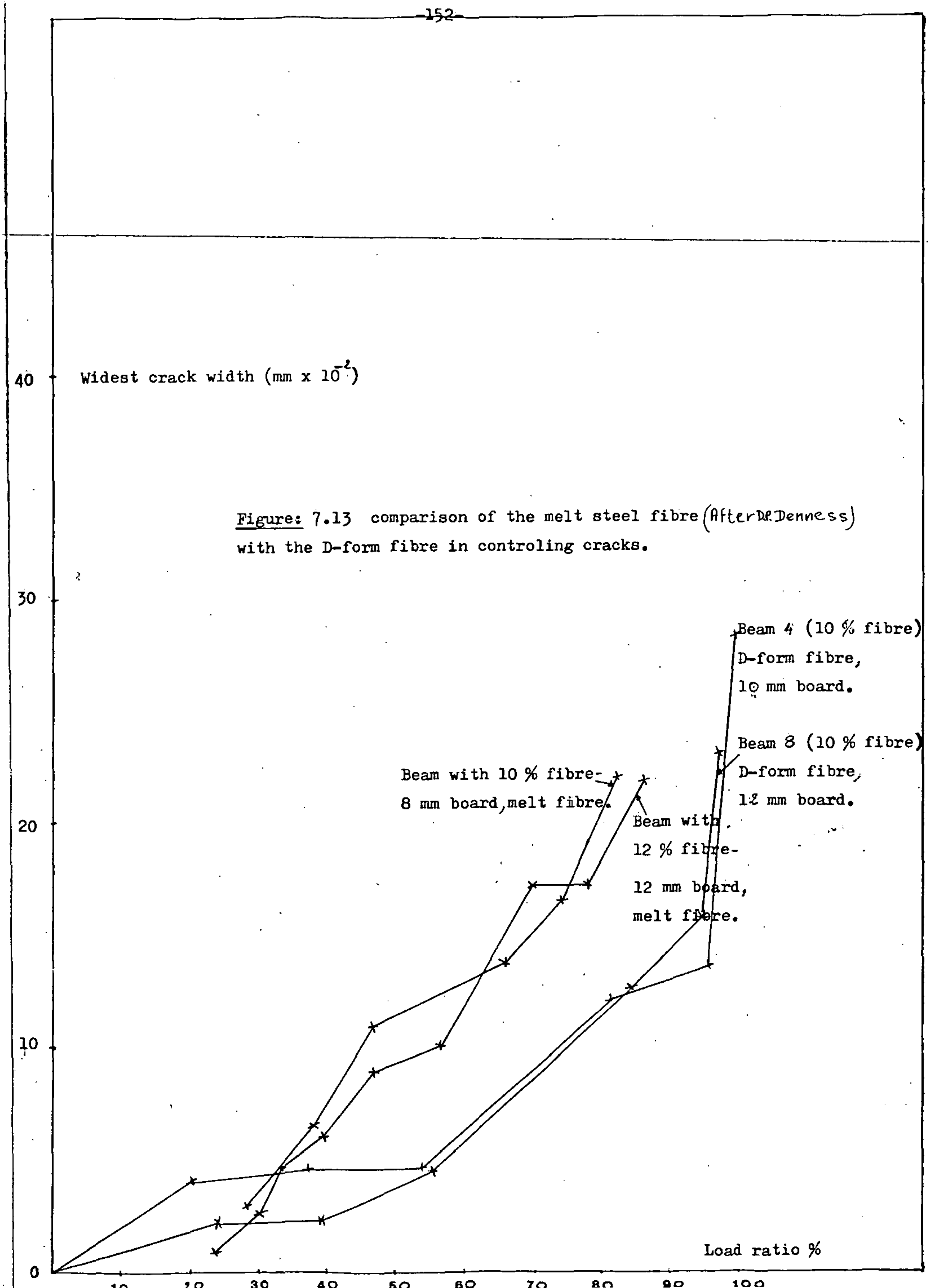


Figure: 7.13 comparison of the melt steel fibre (After Dr. Denness) with the D-form fibre in controling cracks.

ii) Ten per cent fibres by weight of the matrix in the eight mm thick board gave thé best results as crack arrestors;

iii) Increase the number of cracks;

iv) Have no effects on the lengths of the cracks;

v) The twenty five mm D-form fibres have better crack controlling effect than the twenty five mm melt extract fibres.

CHAPTER EIGHT : CONCLUSIONS

8.1 Concrete production

8.11 Mixing and fibre distribution

i) A mixer with a power driven pan was a good mixer for the production of 25mm coarse medium (grade 410) melt extract and 50mm D-form steel fibre cement composites;

ii) For these fibres, it was unecessary to use a fibre dispenser due to the fact that until 10 % by weight of the matrix (12 % in the case of mortar mix) they did not ball.

8.12 Workability and compaction

i) The slump test was found to be suitable to be carried out on site;

ii) The workability of a composite decreases as the fibre content increases;

iii) The workability also decreases as the coarse aggregate content increases;

iv) The melt extract and D-form fibres were found to be more workable than a wide range of drawn steel wire fibres.

8.2 Flexural and compressive strength

i) The increases in compressive strength by the introduction of the melt extract and D-form steel fibres were small when compared to their unreinforced counterparts, whereas, increases in excess of 75 per cent were achieved in the flexural strengths;

ii) The admixture Conplast 337 was found to give an increase in flexural strength in a cheaper manner than by the addition of fibres without loss of workability;

iii) The flexural strength increases with the increase of fibre content;

iv) The 50mm D-form fibres gave higher flexural strengths than the 25 mm melt extract fibres.

8.3 Results of the melt extract and D-form fibres in thin cement composite sheets

i) The modulus of rupture and the limit of proportionality were found to increase significantly with fibre content;

ii) The thinner the depth of the beam, the higher were the modulus of rupture and the limit of proportionality;

iii) The beams tested with the smooth face in tension gave better results than when tested with the latter in compression;

iv) The 25mm melt extract gave higher modulus of rupture and L.O.P. than the 38mm D-form fibres;

v) A modulus of rupture of over 26N/mm^2 was obtained with 6mm thick beams.

8.4 Crack control

The 25mm melt and D-form fibres gave rise to a significant reduction in the maximum width of crack.

The best result in controlling crack was achieved by the use of 10 % by weight of the matrix of D-form fibres in 8mm thick board.

CHAPTER NINE : FURTHER WORK

This investigation was only an introduction to the use of melt extract and D-form steel fibres in cement composites.

I have shown that improvements can be achieved and that the use of these relatively workable fibres increases the flexural strengths. The research also shows that it is possible to replace the time dependant glass fibres in thin sheets.

The experimental work and investigation has shown that there are significant improvements in crack control due to the introductio of these two different fibres.

I would therefore consider the subject area worthy of further research to be focussed on improving and exploiting the above benefits and to:

i) Generalise my design information on workability strength;

ii) To carry out my tests for a longer period of time;

iii) To study also the other properties such as durability, creep, fatigue, shrinkage, impact tests of the melt extract and D-form steel fibres.

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APPENDIX ONE : Compressive and flexural strength results of the melt extract steel fibre composites

Table 1.1 Compressive andflexural strength results of the melt extract steel fibre composites

MIX*	COMPRESSIVE STRENGTHS			FLEXURAL STRENGHTS		
	Av. compressive strength(N/mm^2)	Standard deviation (N/mm^2)	Coefficient of variation	Av. M.O.R. (N/mm^2)	Standard deviation (N/mm^2)	Coefficient of variation
0A75	70.29	3.81	5.42	6.65	0.19	2.86
4A75	61.95	5.02	8.1	7	0.17	2.43
7A75	65.24	3.95	6.05	7.48	0.24	3.21
10A75	66.75	1.62	2.43	7.82	0.24	3.07
12A75	56.50	3.24	5.73	8.39	0.25	2.98
0A50	79.06	2.27	2.87	7.37	0.11	1.49
4A50	62.71	3.63	5.79	7.60	0.26	3.42
7A50	68.16	4.82	7.07	8.06	0.67	8.31
10A50	72.05	3.16	4.39	8.43	0.17	2.02
12A50	59.26	2.88	4.86	9.30	0.44	4.73
0B75	67.66	2.16	3.19	5.83	0.20	3.43
4B75	68.53	2.23	3.25	5.95	0.52	8.74
7B75	72.65	5.68	7.82	7.09	0.28	3.95
10B75	72.61	2.44	3.36	8.20	0.17	2.07
0B50	71.55	0.93	1.3	5.94	0.23	3.87
4B50	79.26	1.97	2.49	6.50	0.22	3.38
7B50	75.37	2.49	3.3	8.22	0.16	1.95
10B50	78.86	2.38	3.02	9.08	0.30	3.3
0C75	62.98	1.5	2.38	4.93	0.15	3.04
4C75	62.58	3.4	5.43	5.82	0.55	9.45
7C75	53.34	0.57	1.07	7.05	0.18	2.55
10C75	63.08	7.4	11.73	8.80	0.26	2.95

Table 1.1 (Continued)

0C50	64.37	2.20	3.42	5.38	0.07	1.3
4C50	63.44	1.36	2.14	6.22	0.17	2.73
7C50	57.82	1.17	2.02	7.30	0.25	3.42
10C50	65.64	1.62	2.47	9.41	0.28	2.98
0D75	83.22	3.82	4.59	6.94	0.15	2.16
4D75	86.91	0.88	1.01	7.79	0.25	3.21
7D75	87.17	1.94	2.23	8.28	0,11	1.33
10D75	100.07	0.71	0.71	9.84	0.16	1.63
0D50	85.5	4.44	5.19	7.70	0.17	2.21
4D50	83.5	4.82	5.77	8.65	0.22	2.54
7D50	81.00	3.04	3.75	9.20	0.10	1.09
10D50	89.00	6.08	6.83	10.40	0.26	2.5
0E75	83.39	2.86	3.43	6.80	0.17	2.5
4E75	78.63	2.58	3.28	7.21	0.28	3.88
7E75	79.30	0.97	1.22	7.80	0.44	5.64
10E75	85.11	2.94	3.45	8.63	0.16	1.85
0E50	88.5	5.1	5.76	7.30	0.23	3.15
4E50	86.25	7.4	8.58	7.79	0.34	4.36
7E50	86.25	3.75	7.83	8.49	0.25	2.94
10E50	87.5	6.25	7.14	9.30	0.25	2.69
0F75	72.32	1.38	1.91	5.87	0.15	2.56
4F75	69.89	2.29	3.28	6.29	0.18	2.86
7F75	73.78	2.06	2.79	6.53	0.21	3.22
10F75	80.36	2.94	3.66	8.10	0.17	2.1

Table 1.1 (Continued)

0F50	76.00	1	1.32	6.04	0.14	2.32
4F50	77.77	4.75	6.11	7.07	0.11	1.56
7F50	75.44	1.22	1.62	7.37	0.15	2.04
10F50	91.39	2.35	2.57	8.36	0.46	5.5

* % by weight of fibres / mix mane / slump in mm at 0 % fibres

APPENDIX TWO : Tables showing the results of the melt extract fibre sheets

Table 2.1 Summary of the results for the flexural tests*

BEAM TYPE**	M.O.R. Mean value ± 90% (N/mm²)	Limit of proportionality ± 90% (N/mm²)	Youngs modulus Mean value ± 90% (N/mm²)	Toughness index. Mean value ± 90% by: Max load criterion	0.8 Max load criterion
6/12/14/T	17.2 ± 4.3	14 ± 2.7	19868.5 ± 10832.6	1.1 ± 0.9	2.06 ± 1.1
6/14/14/T	23.1 ± 5.2	20.8 ± 3.1	28373.7 ± 11344.8	1.3 ± 0.8	2 ± 0.9
6/16/14/T	25.7 ± 3.1	24.6 ± 4.7	25928.8 ± 9345.2	3.1 ± 1.2	3.73 ± 0.9
6/0/14/T	10.6 ± 1.5	9.1 ± 3.2	15637.1 ± 7838.2	1.0 ± 0.9	1.06 ± 0.8
8/12/14/T	13.3 ± 4.6	12.3 ± 2.7	20166.8 ± 9234.9	1.4 ± 0.7	3.64 ± 1.3
8/14/14/T	15.9 ± 3.7	14.4 ± 1.9	19649.7 ± 11784.5	2.1 ± 1.1	4.73 ± 1.7
8/16/14/T	16.8 ± 6.2	15.1 ± 0.9	18615.5 ± 10023.4	3.73 ± 1.2	4.83 ± 1.2
8/0/14/T	7.6 ± 2.6	7.6 ± 2.3	15637.1 ± 7843.4	1.03 ± 0.7	1.06 ± 0.5
12/12/14/T	14.5 ± 4.5	10.5 ± 2.5	22205.7 ± 12001.3	3.1 ± 1.7	4.28 ± 0.7
12/14/14/T	18.3 ± 2.9	14.9 ± 1.8	26901.7 ± 11235.7	2.37 ± 0.8	3.94 ± 1.7
12/16/14/T	20.7 ± 1.7	19.1 ± 0.8	30654.9 ± 9853.8	3.6 ± 0.2	4.67 ± 1.4
12/0/14/T	7.2 ± 2.1	6.2 ± 0.4	14712.3 ± 8740.1	1.05 ± 1.0	1.75 ± 0.5
6/12/28/T	20.7 ± 3.7	18 ± 1.8	26657.4 ± 13451.8	2.23 ± 1.3	4.33 ± 0.3
6/14/28/T	23.8 ± 5.1	21.6 ± 3.7	26527.1 ± 14013.8	2.96 ± 1.9	4.54 ± 0.9
6/16/28/T	26.8 ± 6.3	24.8 ± 4.4	25467.1 ± 13980.8	1.98 ± 1.2	2.66 ± 1.2
6/0/28/T	11.6 ± 4.1	11.6 ± 1.4	21407.9 ± 10371.8	1.3 ± 1.1	2.32 ± 1.3
8/12/28/T	17.3 ± 5.3	15.2 ± 1.3	24170.2 ± 11317.2	2.81 ± 1.1	3.43 ± 1.3
8/14/28/T	18.1 ± 3.8	16.3 ± 2.8	20144.6 ± 9943.5	1.71 ± 1.1	2.7 ± 1.7
8/16/28/T	18.4 ± 9.1	16.6 ± 1.9	15096.7 ± 7834.6	3.01 ± 1.0	4.29 ± 1.2
8/0/28/T	8.8 ± 4.2	8.2 ± 2.2	17452.0 ± 12001.8	1.84 ± 0.8	1.69 ± 0.6
12/12/28/T	15.5 ± 5.3	11.8 ± 1.5	24303.6 ± 13107.4	2.31 ± 1.2	3.18 ± 1.7
12/14/28/T	20.2 ± 6.1	17.8 ± 1.1	32809.9 ± 11314.4	2.15 ± 1.5	2.96 ± 2.1
12/16/28/T	21.9 ± 5.4	18 ± 1.7	29578.0 ± 10451.7	2.95 ± 0.9	3.68 ± 1.4

Table 2.1 (Continued)

12/0/28/T	8.5±1.2	8.3±1.1	20399.5 ± 8843.3	1.0± 0.1	1.23±1.2
6/12/14/C	12.25±2.8	11.1±1.7	20477.0 ± 9752.2	1.7±0.8	1.95±1.5
6/14/14/C	13.6±3.7	13.9±1.3	18936.5 ± 3475.7	1.32±0.6	1.84±1.4
6/16/14/C	14.5±4.8	13.1±2.4	21330.3 ± 10456.6	3.21±1.1	3.2±1.4
8/12/14/C	11.1±5.9	12.2±3.1	20942.4 ± 11939.1	1.3±0.2	1±0.2
8/14/14/C	12.8±4.3	11.2±3.0	17064.2 ± 8399.3	1.22±0.5	3.86±0.1
8/16/14/C	13.8±3.8	12.1±1.1	16592.1 ± 7710.4	2.3±0.2	3.5±0.3
12/12/14/C	10.2±4.2	9.2±2.3	15099.3 ± 8939.3	1.03±0.3	5.9±0.5
12/14/14/C	10.9±3.7	10.2±1.7	18567.5 ± 6934.7	5.01±0.1	2.3±0.3
12/16/14/C	11.7±4.7	11.3±2.1	20826.1 ± 5466.7	5.64±0.6	1.05±0.8
6/12/28/C	14.5±5.1	13.1±1.5	24494.1 ± 10967.6	1.9±1.1	1.8±1.5
6/14/28/C	15.6±4.2	14.2±2.3	21407.8 ± 10873.4	1.71±1.2	2.87±1.8
6/16/28/C	16.1±4.1	15.2±1.9	16288.6 ± 10717.1	1.96±1.6	1.33±0.3
8/12/28/C	12.2±3.1	10.7±2.4	21035.5 ± 11714.8	1.34±1.3	1.59±0.6
8/14/28/C	12.25±1.9	11.3±0.8	20025.1 ± 11213.7	1.2±0.1	3.5±0.5
8/16/28/C	14.2±2.8	13.5±0.7	19014.4 ± 9784.4	1.38±0.8	4.37±0.2
12/12/28/C	10.3±3.7	9.5±1.7	32835.5 ± 13456.1	2.52±1.2	2.39±1.9
12/14/28/C	11.6±4.5	10.4±2.4	31766.8 ± 15312.1	3.01±1.3	3.4±1.7
12/16/28/C	12.4±5.2	11.5±3.5	27532.7 ± 4215.5	2.97±2.1	3.2±1.3

*O.P.C. / Sand = 3.

** Thickness beam (mm) / % fibre by weight / Age (days) / T for smooth face in tension and C for smooth face in compression.

Table 2.2 Summary of the results for the flexural tests*

BEAM TYPE**	M.O.R. Mean value ±90% (N/mm²)	Limit of proportionality ± 90%(N/mm²)	Youngs modulus Mean value ±90%(N/mm²)	Toughness index Mean value ±90% by: Max load criterion	0.8 Max load criterion
6/12/14/T	15.1±5.3	14.7±1.5	24325.2±9128.4	1.84±0.4	2.05±1.2
6/14/14/T	16±4.1	15.2±3.3	24944.7±8347.8	1.38±1.2	1.98±0.4
6/0/14/T	9.9±4.7	9.9±2.1	17600.1±1091.7	1.08±0.9	2.18±0.8
8/12/14/T	12.25±5.2	11.1±2.2	20335.1±6734.9	1.27±1.7	2.12±0.3
8/14/14/T	14.3±5.1	13.1±1.2	21923.4±13931.1	2.07±0.7	3.45±1.9
8/0/14/T	9.8±3.2	9.5±2.3	14933.1±9732.1	1.08±0.9	1.44±1.3
12/12/14/T	10.6±4.5	10±2.1	21789.0±8753.7	2.33±1.3	3.72±1.7
12/14/14/T	11.2±4.6	10.3±1.7	23531.1±9447.3	2.39±1.4	4.25±1.4
12/0/14/T	9.6±2.7	9.5±1.6	14775.5±8744.8	1.18±0.5	2.91±1.9
6/12/28/T	21.25±4.5	18.5±2.1	29744.4±11346.6	2.37±0.3	5.16±1.3
6/14/28/T	24.2±4.1	20.5±2.8	23103.2±13012.4	5.16±1.7	8.72±2.5
6/0/28/T	10.9±5.1	10.9±3.1	20408.8±11089.8	1.10±0.2	1.03±0.4
8/12/28/T	16.2±5.1	14.9±3.4	23457.3±8891.2	1.34±0.4	1.83±1.2
8/14/28/T	19.1±6.2	18±2.6	22517.8±5398.7	1.95±0.9	2.13±1.3
8/0/28/T	10.9±2.9	10.7±1.8	17987.0±6825.5	1.35±1.3	1.09±0.4
12/12/28/T	14.2±1.9	13.6±0.4	23102.9±7243.7	2.24±1.2	1.97±1.2
12/14/28/T	16.8±7.1	15.7±3.9	24455.1±7121.4	2.15±1.5	3.06±0.6
12/0/28/T	10.9±4.4	10.9±2.1	20355.3±9235.6	1.18±1.1	1.03±0.4
6/12/14/C	12±3.4	11.1±1.4	20457.5±11955.3	1.5±1.4	1.27±1.1
6/14/14/C	12.6±4.3	10.9±1.7	19753.4±8734.8	1.41±1.2	1.55±1.2
8/12/14/C	11±2.8	10.5±0.5	19321.4±7450.8	1.34±1.1	1.37±1.3
8/14/14/C	11.6±3.5	11.2±2.4	19923.2±6337.6	1.57±1.4	2.83±1.2

Table 2.2 (Continued)

12/12/14/C	10.2±4.1	9.8±1.4	16763.2± 4021.9	3.44±1.7	3.13±1.3
12/14/14/C	10.7±5.2	9.9±3.5	19375.3± 2102.8	4.38±0.2	5.01±0.5
6/12/28/C	13.9±4.8	11.3±1.8	23474.7 ± 1021.4	1.63±0.8	1.65±0.5
6/14/28/C	15.6±4.9	12.7 ±2.7	22377.3 ± 4373.5	2.11±1.1	2.05±1.2
8/12/28/C	13.3±3.6	12.6 ±2.2	21786.7± 10913.2	1.55 ±1.4	1.83±1.5
8/14/28/C	15.1±3.3	13.7 ±2.1	22365.5 ± 5541.6	1.47±1.2	2.15 ±1.2
12/12/28/C	11.8±4.5	15.5±3.2	31539.9 ± 10838.8	2.15±0.7	1.98±1.1
12/14/28/C	12.4±3.7	11.8±2.1	30935.1 ± 3194.4	1.63 ±0.8	2.07±1.2

* O.P.C./ Sand = 2

APPENDIX THREE : Tables showing the results of crack control

BEAM ONE: 0 % fibre (Reference beam)

LOAD (KN)	Number of cracks	Crack number	Length (mm)	Width (mm)
0	0	-	-	-
6.5	1	1	25	0.043
13	3	1	44	0.115
		2	37.5	0.105
		3	31	0.087
17.5	5	1	69	0.186
		2	37.5	0.137
		3	50	0.152
		4	44	0.187
		5	50	0.112
22.5	5	1	88	0.192
		2	56	0.145
		3	69	0.167
		4	62	0.216
		5	50	0.198
27.5	6	1	81	0.201
		2	72	0.166
		3	81	0.172
		4	75	0.230
		5	69	0.201
		6	56	0.211

BEAM ONE (Continued)

32.5	7	1	106	0.224
		2	72	0.182
		3	94	0.198
		4	75	0.274
		5	81	0.213
		6	75	0.256
		7	31	0.056
33.5	7	1	106	0.231
		2	100	0.201
		3	94	0.215
		4	106	0.377
		5	81	0.223
		6	94	0.262
		7	56	0.114

BEAM TWO : 6 % fibre, 8mm board

LOAD (KN)	Number of cracks	Crack number	Length (mm)	Width (mm)
0	0	-	-	-
8.05	2	1	44	0.043
		2	31	0.033
14	3	1	62	0.080
		2	68	0.144
		3	38	0.153
21	4	1	82	0.098
		2	82	0.216
		3	69	0.184
		4	44	0.056
27.65	5	1	94	0.114
		2	94	0.245
		3	81	0.195
		4	68	0.088
		5	62	0.046
28	5	1	100	0.124
		2	106	0.288
		3	94	0.208
		4	81	0.156
		5	81	0.105

BEAM THREE : 8 % fibre, 8mm board

LOAD (KN)	Number of cracks	Crack number	Length (mm)	Width (mm)
0	0	0	-	-
7	2	1	31	0.029
		2	25	0.023
10.75	4	1	56	0.033
		2	50	0.047
		3	25	0.072
		4	25	0.011
15	4	1	56	0.047
		2	62	0.056
		3	44	0.086
		4	56	0.080
20.5	5	1	76	0.087
		2	82	0.066
		3	69	0.101
		4	74	0.098
		5	45	0.057
25.5	6	1	95	0.103
		2	98	0.098
		3	69	0.173
		4	88	0.123
		5	87	0.125
		6	33	0.034

BEAM THREE (Continued)

31.75	7	1	102	0.153
		2	98	0.125
		3	86	0.230
		4	99	0.136
		5	90	0.159
		6	86	0.068
		7	61	0.045
33.12	7	1	112	0.272
		2	110	0.346
		3	105	0.289
		4	109	0.289
		5	106	0.245
		6	102	0.334
		7	87	0.068

BEAM FOUR : 10 % fibre, 8mm board

LOAD (KN)	Number of cracks	Crack number	Length (mm)	Width (mm)
0	0	-	-	-
7	2	1	24	0.023
		2	23	0.043
12.75	4	1	42	0.023
		2	44	0.047
		3	26	0.023
		4	30	0.011
17.75	5	1	42	0.029
		2	66	0.047
		3	42	0.029
		4	55	0.033
		5	48	0.023
23	5	1	67	0.043
		2	80	0.072
		3	54	0.086
		4	74	0.042
		5	73	0.056
27.75	6	1	80	0.087
		2	104	0.087
		3	68	0.123
		4	74	0.056
		5	73	0.114
		6	26	0.081

BEAM FOUR (Continued)

32.75	7	1	80	0.123
		2	111	0.091
		3	87	0.123
		4	74	0.056
		5	101	0.136
		6	26	0.098
		7	38	0.101
33.25	8	1	104	0.145
		2	121	0.201
		3	87	0.147
		4	89	0.066
		5	120	0.984
		6	26	0.225
		7	44	0.223
		8	83	0.198

<u>BEAM FIVE</u> : 12 % fibre, 8mm board

LOAD (KN)	Number of cracks	Crack number	Length (mm)	Width (mm)
0	0	-	-	-
10.5	2	1	23	0.023
		2	36	0.057
15.5	3	1	37	0.045
		2	48	0.072
		3	25	0.023
20.25	5	1	58	0.045
		2	69	0.130
		3	25	0.091
		4	44	0.045
		5	38	0.023
25.5	6	1	70	0.057
		2	81	0.173
		3	69	0.102
		4	44	0.072
		5	57	0.045
		6	51	0.023
30.25	7	1	88	0.068
		2	94	0.230
		3	82	0.245
		4	44	0.172
		5	83	0.068
		6	51	0.045
		7	49	0.236

BEAM FIVE (Continued)

35.25	8	1	88	0.072
		2	94	0.259
		3	101	0.298
		4	44	0.245
		5	98	0.098
		6	96	0.145
		7	49	0.336
		8	58	0.023
38.5	9	1	88	0.102
		2	107	0.390
		3	101	0.330
		4	44	0.368
		5	98	0.135
		6	93	0.345
		7	49	0.398
		8	58	0.023
		9	86	0.102

BEAM SIX : 6 % fibre, 12mm board

LOAD (KN)	Number of cracks	Crack number	Length (mm)	Width (mm)
0	0	-	-	-
9.25	1	1	19	0.014
13	2	1	32	0.029
		2	18	0.029
18	3	1	50	0.072
		2	31	0.045
		3	32	0.023
22.75	3	1	62	0.072
		2	50	0.056
		3	44	0.098
27.75	4	1	62	0.144
		2	75	0.068
		3	69	0.102
		4	35	0.068
33	5	1	81	0.187
		2	75	0.105
		3	87	0.144
		4	50	0.132
		5	38	0.072

BEAM SIX (Continued)

35.5	6	1	94	0.216
		2	75	0.132
		3	103	0.172
		4	74	0.156
		5	52	0.145
		6	48	0.023
35.75	6	1	95	0.288
		2	75	0.296
		3	103	0.306
		4	74	0.230
		5	52	0.330
		6	94	0.135

BEAM SEVEN : 8 % fibre, 12mm board

LOAD (KN)	Number of cracks	Crack number	Length (mm)	Width (mm)
0	0	-	-	-
7.25	1	1	18	0.014
13.25	2	1	38	0.022
		2	30	0.014
18.25	2	1	58	0.065
		2	43	0.045
23	3	1	69	0.101
		2	62	0.068
		3	44	0.022
28	4	1	81	0.115
		2	69	0.101
		3	57	0.068
		4	38	0.068
32.5	5	1	94	0.201
		2	69	0.156
		3	73	0.108
		4	63	0.072
		5	46	0.101
33.25	6	1	110	0.230
		2	92	0.187
		3	86	0.230
		4	80	0.198
		5	102	0.256
		6	59	0.176

BEAM EIGHT : 10 % fibre, 12mm board

LOAD (KN)	Number of cracks	Crack number	Length (mm)	Width (mm)
0	0	-	-	-
7.5	1	1	24	0.022
12.75	2	1	42	0.022
		2	25	0.014
18	3	1	57	0.029
		2	42	0.045
		3	38	0.029
23	4	1	72	0.068
		2	62	0.098
		3	58	0.056
		4	35	0.072
28	5	1	75	0.105
		2	87	0.123
		3	73	0.085
		4	50	0.098
		5	31	0.056
31.25	6	1	86	0.156
		2	103	0.145
		3	73	0.098
		4	65	0.105
		5	56	0.072
		6	46	0.072

BEAM EIGHT (Continued)

31.5	7	1	86	0.230
		2	105	0.187
		3	73	0.156
		4	68	0.130
		5	75	0.211
		6	47	0.204
		7	54	0.101

BEAM NINE : 12 % fibre, 12mm board

LOAD (KN)	Number of cracks	Crack number	Length (mm)	Width (mm)
0	0	-	-	-
10	2	1	18	0.014
		2	32	0.014
16.25	4	1	38	0.022
		2	50	0.045
		3	30	0.022
		4	24	0.014
22.5	6	1	68	0.045
		2	69	0.072
		3	50	0.045
		4	24	0.056
		5	37	0.022
		6	56	0.056
28.25	7	1	88	0.056
		2	69	0.105
		3	75	0.101
		4	62	0.086
		5	37	0.045
		6	75	0.072
		7	55	0.023

BEAM NINE (Continued)

32.5	8	1	88	0.072
		2	98	0.125
		3	75	0.112
		4	62	0.098
		5	56	0.068
		6	75	0.092
		7	70	0.068
		8	37	0.045
37.5	9	1	88	0.115
		2	98	0.156
		3	106	0.144
		4	87	0.123
		5	56	0.101
		6	75	0.115
		7	91	0.098
		8	93	0.132
		9	86	0.068