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Expert Working Group Meeting on
Fibro-cement Composites

Vienna, 20 - 24 October 1969

# GLASS FIBRE REINFORCEMENT OF INORGANIC BUILDING MATERIALS[1]

by

A.J. Majumdar
India

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## GLASS FIBRE REINFORCEMENT OF INORGANIC BUILDING MATERIALS

by

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Corrigendum 2:

Page 29, Figure 3

Delete LB/IN$^{2}$ in the phrase "Modulus of Rupture - **LB/IN$^{2}$**".

Substitute LBF/IN$^{2}$.

Page 29, Figure 4

Delete LB/IN$^{2}$ in the phrase **"Tensile Strength - LB/IN$^{2}$"**.

Substitute LBF/IN$^{2}$.

Page 30, Figure 5

Delete LB/IN$^{2}$ in the phrase **"Impact strength in LB/IN$^{2}$"**.

Substitute LBF/IN$^{2}$.

Page 30, Figure 6

Delete LB/IN$^{2}$ in the phrase **"Compressive Strength - LB/IN$^{2}$"**.

Substitute LBF/IN$^{2}$.

Page 32, Figure 8

Delete LBS/IN$^{2}$ in the phrase **"Tensile stress lbs/in$^{2}$"**.

Substitute LBF/IN$^{2}$.

Page 26, Reference 26

Delete (In press, to appear in Mag. Concrete Res., 1969).

Substitute Magazine Concrete Research, vol. 21 (66), March 1969, pp. 23-30.

## 1. Introduction

The demand for new materials is a demand for mechanical strength in engineering construction. Inorganic building materials like cements and concrete possess adequate compressive strength but their inherent weakness in tension and against impact seldom permit effective utilisation of their high compressive strength in structural applications. This weakness is conventionally overcome by strengthening these matrices with steel and the technology of reinforced concrete, both ordinary and prestressed, forms an important branch of civil and structural engineering today. A rather different type of material is produced when cements and concrete or gypsum plaster are reinforced with a suitable fibre. Asbestos-cement products extensively used in the building industry provide an example of this type of material which is described as a composite material. Ferro-cement, originated by Nervi (1) in 1947, consisting of layers of fine steel mesh, one on top of the other and impregnated with cement mortar, is another example of an inorganic composite material known to the building technologist. The most familiar example of a true composite material used in buildings is, of course, glass fibre reinforced plastics.

In search for strength in new materials, three separate properties are required: elastic stiffness, resistance to plastic deformation and resistance to fracture. It is usually very difficult to achieve all three properties in the same material and much of the present research activity in fibre-reinforcement is aimed at solving these problems. The principles of fibre reinforcement of metals and plastics are now fairly well understood and a number of excellent reviews is now available (2, 3). Inorganic building materials, however, do not undergo pronounced plastic deformation like metals; nor can they be deformed much by elastic extension as in organic polymers without fracturing. In addition, contrasted with the other two types of material these matrices are highly porous. Consequently, the mechanisms of reinforcement by which the superior mechanical properties of fibres can be exploited to produce strong cement-based composites are not very well understood. Krenchel (4) has pioneered much of the thinking in this area. The problems in fibre reinforcement of cements and concrete are very similar to those found in the field of ceramics and these have been pointed out recently by Bowen (5), and by Majumdar and Ryder (6). Broadly speaking, in view of the very porous nature of the matrix a relatively small (∿ 10 wt%) percentage of fibre can be efficiently incorporated in these materials. The bond that develops at the interface is discontinuous in nature (7) and its strength (8) depends rather strongly on porosity. These factors ultimately control the improvement in mechanical properties that can be achieved by fibre strengthening of these materials. In addition, inorganic cement matrices crack at very low extensions and it is very doubtful if very stiff and/or very strong composites can be prepared with them unless their mechanical properties are drastically altered.

## 2. Selection of Fibres

In order to meet the materials needs of sophisticated industries such as the aero-space industry, whiskers and fibres of very high strength and stiffness have been developed. The latest and perhaps the most important arrival is the carbon fibre (9) which can be produced in continuous lengths. Because of the very high cost of these fibrous materials at present, it is unlikely that they will find application for reinforcing cements and concrete in the forseeable future. From the point of view of economic viability three types of fibres offer promise of immediate application. These are metal, e.g. steel fibre, polymer, e.g. polypropylene fibre, and glass fibre, and vigorous research has been going on in various countries over the last few years on the practicability of developing a cement based composite material reinforced with these fibres. Following Nervi (loc. cit), Romualdi (10) and co-workers have studied reinforcement of concrete by 0.15mm diameter short steel fibres and have obtained satisfactory composite action. Goldfein (11) has published data which show that excellent impact strength can be achieved in cement based composites by the incorporation of organic polymer fibres and Shell Chemicals claim to have developed (12) a new product 'Caricrete' which is concrete reinforced with fibrillated polypropylene.

The current interest in reinforcement of cements by glass fibres stems from the very encouraging results reported by Biryukovich and co-workers (13) for such composites. Resin-bonded glass fibre tendons as a substitute for steel wires had previously been considered, among others, by Rubinsky (14). The work in the USSR over a decade and summarised by Biryukovich et al (13) indicated that special cements such as gypsum-aluminous slag-cements and high-alumina cements manufactured in the USSR can be successfully reinforced by the commercially available low-alkali borosilicate glassfibres such as the E-glass fibre but the use of Portland Cement, which is much more corrosive, leads to failure of the glass fibre reinforcement. The Russian authors suggested that for use with Portland cements (they are by far the most important type of cement in construction use) presently available glass fibres must be protected by an alkali-resistant coating. Very recently (15) commercial success has been claimed for one type of specially coated glass fibre for application in concrete, although durability results of this product 'Fycrete' have not yet been published.

Experimental results obtained at the Building Research Station (16) confirm the findings of Biryukovich and co-workers (13) that Portland cements and low alkali borosilicate glass fibres do not make durable composites. We have suggested that for applications with Portland cements special glasses with very high degrees of alkali resistance must be developed and one such glass fibre (6, 16) having composition in the $Na_2O$ - $SiO_2$ - $ZrO_2$ system has given promising results. It has also been shown (17) that gypsum-plaster is a very suitable matrix for reinforcement with commercially available fibres (e.g. E-glass).

Properties of some of the fibres discussed in this paper are listed in Table 1.

TABLE 1 PROPERTIES OF FIBRES

| Fibre | Sp. Gr. | Tensile Strength ($Kg/cm^2$) | Young's Modulus ($Kg/cm^2$) | Chemical Compatibility with Portland Cement | Availability | Approximate price (per Kg)(a) |
|---|---|---|---|---|---|---|
| Asbestos Minerals (b) | | | | | | |
| Chrysotile | 2.55 | 31,000 | $1.65 \times 10^6$ | Good | Abundant, mostly in Canada and USSR | 20 US cents |
| Crocidolite | 3.37 | 35,000 | $1.9 \times 10^6$ | " | Limited | 20 " |
| E-glass | 2.56 | ~ 20,000 | $0.75 \times 10^6$ | Poor | Unlimited | 60 " |
| High tensile steel | 7.8 | ~ 17,000 | $2.0 \times 10^6$ | Good, but corrodes in thin sheets | Unlimited | 75 " |
| Polypropylene (c) | 0.91 | ~ 4,500 | $\sim 0.03 \times 10^6$ | Excellent | Unlimited | 80 " |
| Sisal | 1.45 | ~ 1,350 | $\sim 0.12 \times 10^6$ | Unknown | Very limited Mostly in Eastern Africa | 18 " |
| Carbon (Modmor Type 1) | 1.99 | ~ 20,000 | $4.4 \times 10^6$ | Excellent | Very limited at present | very expensive |

(a) Prices quoted are United Kingdom prices.

(b) Fibrous Silicates by A A Hodgson, The Royal Institute of Chemistry, Lecture Series, No. 4 (1965).

(c) Reference 12.

It must be stressed here that from all points of view, i.e. high stiffness, high strength, chemical durability and low cost, asbestos minerals provide excellent materials for reinforcing cement and concrete. They suffer from the very serious drawback that they are mainly available in very short lengths (< 7 mm) and as a result the composites made with them have poor resistance to impact. A crystalline silicate material with mechanical and chemical properties similar to those of the asbestos minerals but which could be produced in continuous lengths and which will not be hazardous to health like asbestos would be, in the author's view, a very suitable material for reinforcing cement and concrete. A research programme aimed at producing such a fibre is in progress at the Building Research Station.

## 3. Theoretical Considerations

In a fibrous composite material where infinitely long fibres are aligned parallel to the tension axis and uniformly distributed in the matrix, but are not in contact with each other and where the interfacial bond is continuous in character, the value of the Young's modulus of the composite $E_c$ is given by the lower bound of the Voigt estimate (18) when the values of the Poisson's ratio of fibre and matrix are identical. For the cases under consideration, i.e. glass fibre reinforced cements (grc) and plaster (grg), Poisson's ratio of the fibre is 0.22 and that of the cement paste lies in the range 0.20 - 0.30 depending on the water/cement ratio (19). The mixture law is, therefore, applicable for these composites in the elastic range. This relationship states that

$$E_c = E_f V_f + E_m V_m \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \quad (1)$$

where E and V are Young's modulus and volume fraction and subscripts f and m refer to the fibre and matrix phases respectively. Also, in the case of these composites reinforced with continuous fibres, where the critical fibre volume fraction is extremely small (due to the very low (0.02 - 0.06 per cent) breaking strain of the matrix) and where there is virtually no plastic flow in the matrix itself, the tensile strength in the direction of the fibre alignment is given by the expression

$$\sigma_c = \sigma_f V_f + \sigma_m V_m \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

This relationship is applicable for conditions of equal elastic strain in fibres and matrix.

Krenchel (4) has shown that in the case of composites where fibre orientation is random and/or where reinforcement is effected by short, discontinuous fibres, mathematical expressions given in equations 1 and 2 for mechanical strength of composites have to be modified and he has derived suitable 'efficiency factors' for different fibre orientations in the composite and introduced a length efficiency factor in a manner similar to that given by Kelly (20). Maries and Tseung (21) have very recently summarised the current views on the probable modes of failure of grc and have listed analytical expressions for computing mechanical properties of these materials. The usefulness of these calculations has also been discussed by the present author elsewhere (6).

## 4. Fabrication methods

The role of a suitable method of fabrication is critical in the manufacture of composite materials as their mechanical properties depend very much on it. As far as grc and grg products are concerned, fabrication methods used in the reinforced plastics (grp) industry are both convenient and practical whereas the methods used in the asbestos-cement industry are less efficient as in this case the fibres tend to ball up during the mixing operations. Although in the development of suitable theories for fibre reinforced cement-based composites it is necessary to concentrate on uniaxial reinforcement by continuous fibres, from the practical point of view of application in the building industry it is important to consider random distribution of fibres as well. In this respect the manufacturing methods developed by the technologists in the USSR which are described fully by Buryukovich et al (13) have been very successful. Broadly speaking, conventional grp techniques such as contact moulding, chopped strand spray-up or filament winding can be used with minor modifications necessary to take into account the particular physical properties of the cement paste. The selection of a particular method depends on considerations of cost, type and quality of the product and the extent of automation envisaged. Uniaxially reinforced flat sheets of grc and grg materials can be produced by splitting the cylinders formed (by filament winding technique) on the winding drums in the green state or alternatively they can be bent, also in the green state, to fabricate corrugated sheets or other shaped products. Chopped glass fibre strands and cements or plaster can be premixed before moulding or spray-up; mats, fabrics or glass fibre rovings can be impregnated with cement paste before they are processed by a particular method of manufacture.

Research at the Building Research Station (16, 17) has shown that for fabricating grg and grc composites it is best to use a high water-binder ratio so that the slurry can be readily worked. Some method has to be devised then for removing the excess water. Suction, pressing and centrifuging are all possible methods and the first two techniques have been successfully employed. In the spray-suction method developed at the Station (22) a combined spray of cement or plaster slurry and chopped rovings up to 50 mm length is distributed over the surface of a perforated metal mould lined with high wet-strength paper. The glass fibre chopper is mounted on a spray gun which is attached to the pump transporting the slurry. The mould has adjustable screed boards all round so that sheets of various thickness can be fabricated. The material is usually sprayed until a thickness of 10 - 15 mm is reached and the top surface is then levelled off with a straight edge. The excess water is then extracted by the application of suction of 0.07 - 0.08 $N/mm^2$ for five minutes. Immediately after suction the sheet is demoulded and stored under normal laboratory conditions. GRC panels are covered with a polythene sheet for the first few days. The fibre/binder ratio can be changed by controlling the number of strands chopped in a given time. It is also possible to alter the length of the chopped fibre by varying the number of cutting blades in the chopper drum.

The composite material produced by the spray-suction technique appears to have a structure in which the fibres are randomly distributed in a plane. The method is quite rapid; a 1.5 x 1 m x 10 mm panel taking about seven minutes and the technique will lend itself to automation easily. The essential features of the process can be seen in the photograph marked as Fig. 1. The process is also quite versatile and is limited only by the feasibility of providing a suitable mould for the article to be made. Pumps, choppers etc. are standard equipment available commercially. Using grg material it has been possible to manufacture full-scale prototypes of structural partitions, floor and ceiling units, fire check doors and door frames etc. Some of the items made in grg are shown in the photographs designated as Fig. 2. The Russian authors (13) have also listed several components which they fabricated using glass fibres and a special cement.

Composite boards have also been made on the Station's concrete press by spraying plaster or cement slurry and chopped roving on to the paper lining of the perforated bed of the press and then subjecting the mix to a pressure of 2.8 $N/mm^2$ to squeeze out the excess water. This technique provides more efficient dewatering and produces better compaction of the composite, but the press is expensive and only flat sheets can be produced in this way. In this method of manufacture it is also possible to use chopped strand mats, specially woven fabrics, surface tissue etc. as the reinforcement. They can be impregnated in the cement slurry prior to pressing. It should be emphasised that the utilization of the reinforcing effect of fibres randomly distributed is considerably lower than with unidirectionally arranged fibres. Random arrangements of short fibres in the matrix produce an isotropic material when fabricated as thin sheets and they have the great advantage in practical applications in that the fabrication technique is simple and therefore less costly. On the other hand a linear distribution possibly permits a greater volume fraction of the fibre phase to be incorporated. The orderly arrangement facilitates the packing process. When high structural strength is desired in a specific direction in a structure, uniaxially aligned glass fibre strands can be used to provide this directional reinforcement, and this can be done in conjunction with a homogenous grc matrix also.

Although it is felt now that the main application of glass fibre lies in grc products which could have applications similar to asbestos cement, attempts are being made in several countries (12, 15) to study the feasibility of incorporating these fibres in structural concrete. The main problem here seems to centre on the difficulty in dispersing the fibre uniformly in concrete using existing concrete mixing techniques. Fibres tend to knit into balls when mixed in the usual concrete or mortar mixers. Thus it is normally found that 2 per cent by volume is seldom exceeded on account of this tendency. It is also feared that coarse aggregates would damage brittle glass fibres by mechanical attrition during the mixing process so that their tensile strength would be greatly reduced. It has also been found that concretes with small diameter fibres dispersed in them require a considerably higher overall water content to give the same workability as concretes without any fibres. This factor also reduces the strength of the concrete. In conventional concretes, incorporation of chopped short fibres in a random way to the extent of 2 - 4 per cent by volume does not lead to any significant improvement in the tensile strength properties. The impact strength and shattering resistance are, however, improved as compared with plain concrete. It is felt that for improving the structural strength of concrete by glass fibre reinforcement it would be necessary to design a new type of concrete mixer which will take into account the specific requirements of the fibre dispersion process so that greater volume fractions of fibres can be incorporated in concrete.

## 5. Testing of grc and grg composite materials

Nearly all countries in the world have their own Standards Institutions which provide standards and define codes of practice for materials to be used in buildings. Such standards and codes of practice are available for cements, plaster, concrete and in countries where asbestos is used in large quantities for asbestos-cement products. A discussion of these various standards and codes of practice is not necessary here as this information is readily available from respective Standards Institutions in these countries. For composite materials based on cements or plaster and reinforced by glass fibres no similar standards or codes of practice have been formulated yet since these materials are very new and have yet to pass the research and development stage. It is hoped that appropriate actions will be taken by responsible Government bodies when these materials have proved themselves in trial semi-industrial applications in terms of strength and durability.

Among the composite materials in use today in the building industry glass fibre reinforced plastics and asbestos-cement products are by far the most important. A detailed account of the various tests that are required to establish the properties of grp has been given by Prosen (23). Both destructive and non-destructive testing methods have been considered and the importance of testing judgement and the analysis of data have been duly stressed. Methods of standardising the strength of asbestos-cement products have also been described. (24).

At the research and development stage, a new material need not be examined so critically and only the more important properties of the material need be determined and assessed relative to a standard material which is similar to the material being developed. For both grg and grc composites research at the Building Research Station has followed this approach and performance of the composite material has been evaluated by comparing the results obtained with them, with those of the unreinforced material. For grc composites, asbestos-cement sheets have served as a convenient standard. If the specimen size, testing conditions etc. are kept the same for both the standards and the new composite materials, it is possible to obtain quantitative data on the properties of the materials being studied.

Among the tests carried out routinely at the station on glass fibre reinforced inorganic building materials, measurements of mechanical strength, physical properties such as density and an assessment of the chemical durability of the composites are the more important ones. For cement based materials durability is perhaps the most important consideration. Test speciments of such materials are stored in air and under water in constant temperature and humidity conditions and tested at specified ages up to two to three years. These specimens are also subjected to natural weathering in the Station's exposure site so that effects of cyclic wetting and drying and/or freezing and thawing can be studied. There are, at present, no standards for an accelerated test for durability of concrete. In order to gain some knowledge of the chemical compatibility of the fibres and cements, uncoated single filaments of glass are exposed to chemical attacks by the aqueous phase of the Portland Cement slurry at 80°C and the tensile strength of the corroded fibres is measured (25) as a function of time. Details of these tests have already been given (16). Specimens of the composite material made from cements are also kept in a laboratory oven at 50°C and their strength measured at specified ages. These results provide some estimate of the accelerated attack on the glass fibre by the cement slurry and may be correlated with the long-term durability of these materials.

Mechanical strength testing includes determination of elastic properties, flexural, tensile and compressive strength of these materials and measurement of their resistance to failure by impact. Test specimens are sampled in a random way and effects of experimental variables are studied by a factorial analysis of variance. Details of these testing schedules, specimen sizes etc. have been recently described by Ali and Grimer (17) for grg material. With these materials some tests on their creep and fatigue properties have also been carried out. The test procedures are exactly the same in the case of grc materials but in this case a long-term testing programme is absolutely essential for assessment of the durability of these products. All mechanical testing has been done on a universal testing machine such as the Instron which is provided with many ancillary equipments necessary for specific tests. For impact tests a specially designed Izod-type machine (17) has been used.

Glass fibre reinforced gypsum plaster panels have also been subjected to fire tests in a box furnace the temperature of which was raised at a rate conforming to British Standard 476.

## 6. Properties of grg and grc composites

### GRG composites

Hemihydrate gypsum plaster ($CaSO_4.\frac{1}{2}H_2O$) is commercially available in two modifications - plaster of Paris or the β-hemihydrate and the α-hemihydrate which is produced by an auto-claving process and which produces a workable mix at a lower water content. In a recent programme carried out at the Station both forms of plaster have been used and since the α-form is more expensive some experiments used a 50:50 mixture of α and β-forms. A plaster slurry made with either α or β hemihydrate does not attack glass fibres chemically. Commercially available glass fibres (E or A-type) can therefore be used for strengthening the plaster mix.

Much of the data on the physical and mechanical properties of the grg material collected in this laboratory over the last two years has already been published (16, 17). Results obtained by Ali and Grimer (17) with grg materials produced by the spray-suction technique are depicted in Figures 3 to 7. These results show that for composites made in this manner where the fibres are distributed randomly in a plane parallel to the face of the mould, both tensile and bending strengths reach maximum values at certain fibre volume percent additions and then fall off. In contrast, the compressive strength decreases even when a small amount of fibre has been added. According to Ali and Grimer this is due to increase in the porosity of the material. The density of the material also passes through a maximum with increasing fibre percentage. The impact strength, on the other hand shows a linear improvement with fibre addition as seen in Fig. 6. The increase in impact strength was twenty to thirty times the plain plaster strength for a glass content of 10-12 per cent. This improvement is due to the crack-arresting mechanisms (5) induced in the composite by fibre incorporation.

Composites which were fabricated from a pre-mixed slurry by pressing gave strengths which were inferior to those made by the spray-suction technique. Since in this case the distribution of the fibre is supposedly three-dimensional random, these low strength values are to be expected. The effects of fibre length and compaction pressure on composite properties were determined with these samples and some of the results are listed in Table 2. There is some indication that longer fibre lengths produce stronger and less brittle composites. These properties appear to be less sensitive to small changes in compaction pressure.

TABLE 2 PROPERTIES OF grg COMPOSITE AS AFFECTED BY FIBRE LENGTH AND COMPACTION PRESSURE

| Fibre % (by wt) | Fibre length (mm) | Flexural Strength $N/mm^2$ | | | Impact Strength ($Nmm/mm^2$) | | |
|---|---|---|---|---|---|---|---|
| | | Compaction pressure ($N/mm^2$) | | | Compaction pressure ($N/mm^2$) | | |
| | | 0.7 | 2.0 | 5.0 | 0.7 | 2.0 | 5.0 |
| 6.4 | 11 | 28 | 27 | 27 | 18.5 | 16 | 16 |
| 6.2 | 22 | 27 | 31 | 33 | 20 | 19.5 | 18 |
| 6.4 | 34 | 27 | 26 | 28 | 20 | 20 | 19 |
| 6.2 | 44 | 32 | 32 | 34 | 22 | 24 | 19 |

The stress-strain behaviour of grg composites in tension is illustrated in Fig. 8 at two glass levels. Both composites were made by the spray-suction method. Assuming a tensile strength of the order of 3 $N/mm^2$ for the unreinforced material, the improvement in the tensile strength at the elastic limit caused by fibre addition is modest whereas the ultimate strength is approximately four times at the higher fibre volume fraction. Fig. 8 also shows that even with low per cent of fibre addition, grg composites behave like a quasiplastic material. It is, therefore, possible to increase the working stress level without any danger of sudden disastrous failure.

A preliminary fire test carried out in accordance with BS 476 on a 7 mm thick grg panel has shown that up to about one hour there is no penetration of the flame when one face of the panel is exposed to a temperature of 900-1000°C. This performance compares very favourably with that of a normal 10 mm thick paperfaced plasterboard which collapses in this test in 15 minutes.

The properties of grg suggest that in selecting components for development it is better to consider it as a fire-resistant alternative to timber than as a substitute for reinforced concrete. The tensile strength is about quarter that of timber along the grain but four times that of timber across the grain. The two materials are comparable in impact strength whilst the modulus of elasticity of grg is about 1.5 times that of timber. Some of the components made with grg material can be seen in the photograph in Fig. 2. The strength and rigidity of a double-skinned floor unit measuring 3.9 m x 1 m x 130 mm and having approximately 7% by wt. of glass fibre are illustrated by the load-deflection curves in Fig. 9. Panel 1 was tested to destruction under uniformly distributed loading on a span of 3.7 m. The unit deformed elastically up to a load of 7.6 KN/m$^2$ and showed a mid-span deflection of 12 mm. Deflection at the failure load of 16.2 KN/m$^2$ was 150 mm and the collapse of the unit was gradual rather than sudden. Panel 2 was subjected to four non-destructive static loading tests under 1/3rd point loading. The first and second static loading were carried out before any repeated loading cycles were introduced. The third and fourth static loading were carried out after the panel had been subjected to 0.5 million cycles of 1.3 to 1.6 metric tons of equivalent uniformly distributed load. No appreciable permanent deformation was noticed after this dynamic loading test.

The strength and fatigue characteristics of the floor units made them suitable for use in two-storey buildings.

GRC Composites

In the case of glass fibre reinforced composites based on silicate or aluminate cements, the most comprehensive study reported so far was carried out in the USSR by Biryukovich and co-workers (13). However, the cement for which a wealth of information is now available as a result of these studies is a special cement made from an aluminous blast furnace slag to which 30 per cent of gypsum is added. There has also been a suggestion in these Russian reports that high-alumina cements and borosilicate glass fibres also give durable composites.

Results with high-alumina cements of British origin are not as encouraging as once thought (16). Grimer and Ali (26) have studied these composites over a long period of time and some of their results are given in Figs. 10 and 11. Details of the properties of the cement and the fibre and the method of fabricating the composites can be found in the paper by Grimer and Ali. Similar data for the Russian cements have been given by Biryukovich et al. (13).

From the relationships of strengths versus age for various glass contents (Fig. 10) it is evident that these composites reach their maximum strength at a certain age depending on the fibre volume fraction present as reinforcement. Although the maxima in these graphs show quite clearly that successful composite action can be achieved between high-alumina cement and E-glass fibre, the substantial drop in strength over long periods of time does not make this material suitable for use in building. Assuming a bending strength of 25-30 N/mm$^2$ for superior grade asbestos cement sheets, it is quite clear that similar strengths can be ensured easily for grc with 5-7 per cent by wt. of fibre addition in short-term applications and the product may also be economically viable. But for long-term applications the durability of the high-alumina cement based composites must be improved. Such a study is in progress at the Building Research Station.

The impact strength of grc composites compares very favourably with that of asbestos cement (typically, 2 Nmm/mm$^2$) although the improvement due to fibre addition is not as marked in the case of grc as it is in the case of grg. The variation of impact strength of high-alumina cement composites with age is shown in Fig. 11 for several glass levels. Again, a progressive deterioration in the performance of this material has been recorded. Like the bending strength, the maxima in the strength versus age plots move progressively to later ages with increasing glass content.

With other types of cements, e.g. ordinary Portland cements or supersulphated cements both of British origin grc products made with E-glass fibres have shown properties similar in character to those illustrated by Fig. 10 and 11. It seems that at the present moment there is not available any commercially manufactured glass fibre which will give durable grc products. This is essentially due to chemical corrosion suffered by the glass. In several laboratories work is in progress which is aiming at producing more alkali-resistant fibres either by alteration in glass composition or by coating them with a suitable material or by both.

## 7. Composites in underdeveloped countries

The problems associated with reinforcement of building materials in developing countries are complex and vary enormously from country to country. In general, cities and urban areas in these countries use building materials and methods which are very similar to those in vogue in the more developed parts of the world while in rural areas indigenous materials and building methods find extensive application mainly due to economic reasons. Any assessment of the potentialities of fibre reinforced composite materials such as grc or grg must take this overwhelmingly important consideration into account. The other major consideration is that of the level of technical skill available in these countries. There is such wide variation in this respect in different technologically underdeveloped regions of the world that it is virtually impossible to arrive at any generalised set of recommendations.

Among composite materials based on inorganic cements which are used on a large-scale in technologically underdeveloped countries, asbestos-cement products are by far the most important. Asbestos-cement roofing sheets, pipes etc. are quite well-known to the building trade in these countries but unfortunately in none of these countries, natural asbestos is available in economically significant quantities. More than 90 per cent of the world's known asbestos deposits are to be found in three regions, Canada, USSR and southern Africa. The needs of the developing countries have to be met, therefore, by imports. The prospect of substituting asbestos in cement applications with other fibrous materials, although not certain at the moment, is a real one and once this breakthrough is established, those regions of the world which do not possess asbestos will greatly benefit.

Apart from asbestos-cement products grc should find applications in certain structural components also. Various shell or folded-plate structures, water-storage tanks etc. can be constructed with this new material. Provided the durability of grc composite materials is proved to be satisfactory, engineers and architects will be able to design building components with this material taking into account their structural strength characteristics which can be varied within wide limits to suit particular design features. In this respect the possibility of prestressing with resin-bonded glass fibre rods should also be explored.

Regarding application in rural areas of developing nations, one has to take notice of the fact that dwellings in these parts use mud plasters, timber plus foliage etc. as the basic materials of construction in preference to cements and/or bricks for reasons of availability and economic considerations. This practice will continue for some time to come until higher cement and brick production consequent upon industrialisation in these countries permit the adoption of these materials for construction of semi-permanent houses in these areas. For the present, much research has already gone into waterproofing (27, 28) mud plaster and application of these results on a large scale is foreseen.Even in the constructions of these mud huts some fibres already play a valuable role. These are vegetable fibres (29), locally available, which are mixed with mud plaster to give it more rigidity. They also provide reinforcement in sun-dried bricks. They are also used extensively in the construction of roofs. These agricultural fibres are, however, not very durable and their use as roofing material introduces fire hazard but for the present moment use of more stable fibres such as asbestos or glass can be ruled out on the grounds of non-availability and higher costs.

However, if one takes a very long-term view, one has to accept that these rural regions of the developing countries will also be semi-industrialised one day and one has to submit to the suggestions that composite materials based on cements will find wide applications then. In view of its extremely low cost of production and in spite of the very high capital investments involved, manifold increase in cement production should be the top priority wherever availability of raw materials allow installation of such plants. The same applies to production of household bricks.

Compared to their needs, cement is in short supply in most developing countries and serious efforts should be made to stop wastage of this material. Wherever possible, cements should be diluted with pozzolanic materials such as perverised fuel ash, sintered clay and even addition of special types of soil to cement for structural use may be practical. This diluted type of cement would be a suitable material to replace mud-plaster with and it can be conveniently reinforced by suitable fibres. Reinforcement by steel wire, asbestos-type fibres, alkali-resistant glass fibres or strengthening by strong vegetable fibres such as manila hemp or sisal can then be considered. However, even the medium-term durability of agricultural fibres in cements is suspect, and research along these lines should be carried out in these countries in depth. Also, the relative cost of installing sophisticated fibre industries such as glass fibres or polypropylene fibres should be assessed vis a vis that of reinforced concrete.

Some form of fibre reinforcement may also be used advantageously in the precast concrete industry. With industrialisation, many developing countries will turn to these products on an increasing scale and their use in semi-rural industrial townships is easily foreseeable. It is well-known that the breakage rate of precast concrete units is fairly high even in technologically developed countries and some form of handling reinforcement is being seriously considered.In developing countries, this will be all the more important since transportation is more difficult in these areas, and works through-put is more important ~~that~~ than materials cost. In this respect, potentialities of local vegetable fibres such as sisal or even coconut fibres should be explored.

The discussion in this section has centred on grc rather than grg products for the obvious reason that the former is considered to be more applicable for developing countries. However, if gypsum plaster is available and can be used in indoor applications, current research at the Station has amply demonstrated the feasibility of fabricating load-bearing components with plaster after strengthening it with glass fibre.In arid regions grg may well be suitable for external applications. Fibrous plaster reinforced with sisal or flax is extensively used in Australia and New Zealand (30) and grg products can be designed to provide a whole range of building components. The prospects of wide-spread use of both grc and grg products in pre-fabricated buildings seem very bright.

The fabrication techniques to be used in the manufacture of grc or grg composites are fairly simple and should not pose any special problem for the more technologically advanced countries like India and Pakistan, certainly not in urban areas.The experience in Australia and New Zealand with 'fibrous plaster' has shown that manufacture of building components with grc and grg materials can be profitably organised as cottage industries. Both semi-skilled and unskilled labour can be utilised in these industries in an efficient way. Since most developing countries have large reserves of unemployed or underemployed labour and where labour costs are still very low when compared to materials or capital outlay this aspect of the composite industry should also prove attractive to policy makers and industrialists in these countries.

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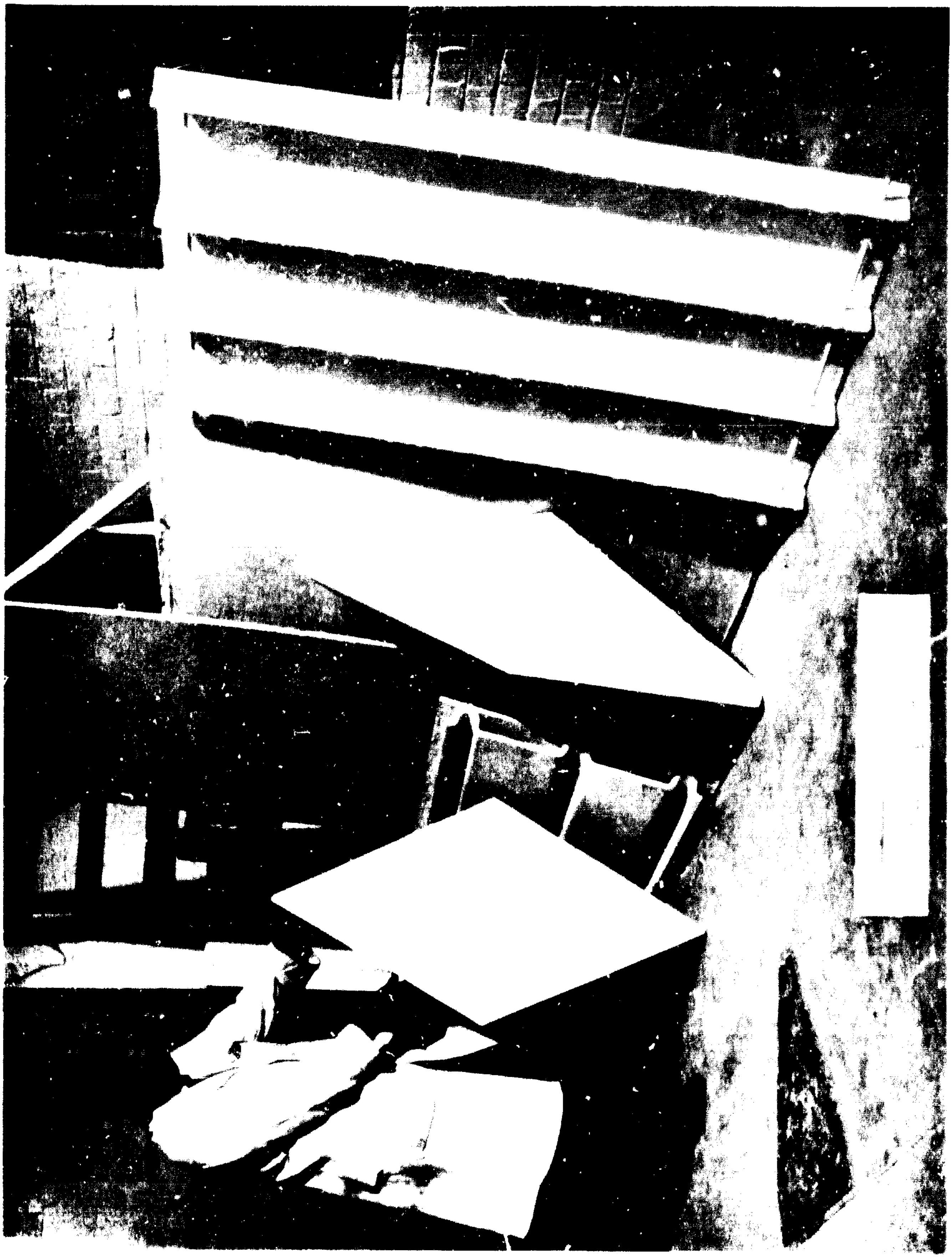
Figure 1

Fabrication of composites by spray-suction technique



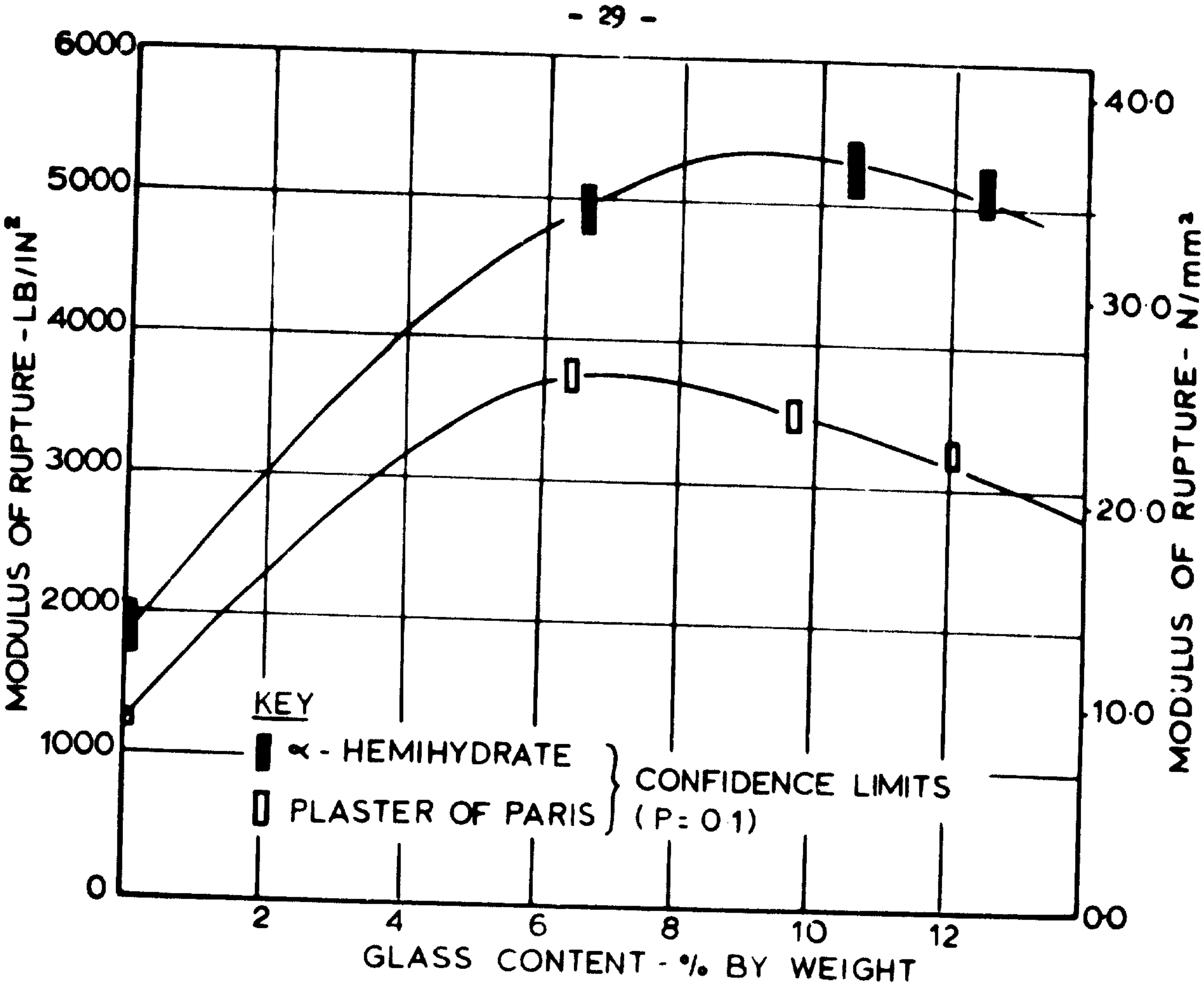


FIG. 3 RELATIONSHIP BETWEEN MODULUS OF RUPTURE AND GLASS CONTENT FOR GLASS FIBRES IN GYPSUM PLASTERS

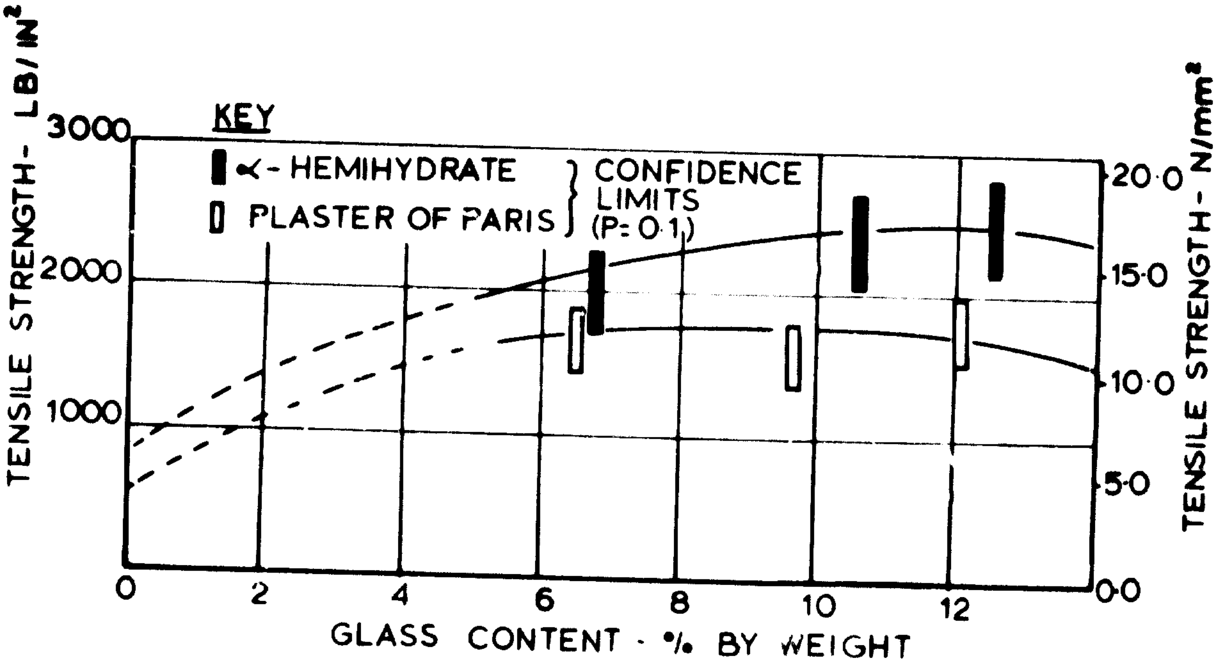


FIG. 4 RELATIONSHIP BETWEEN TENSILE STRENGTH AND GLASS CONTENT FOR GLASS FIBRES IN GYPSUM PLASTERS

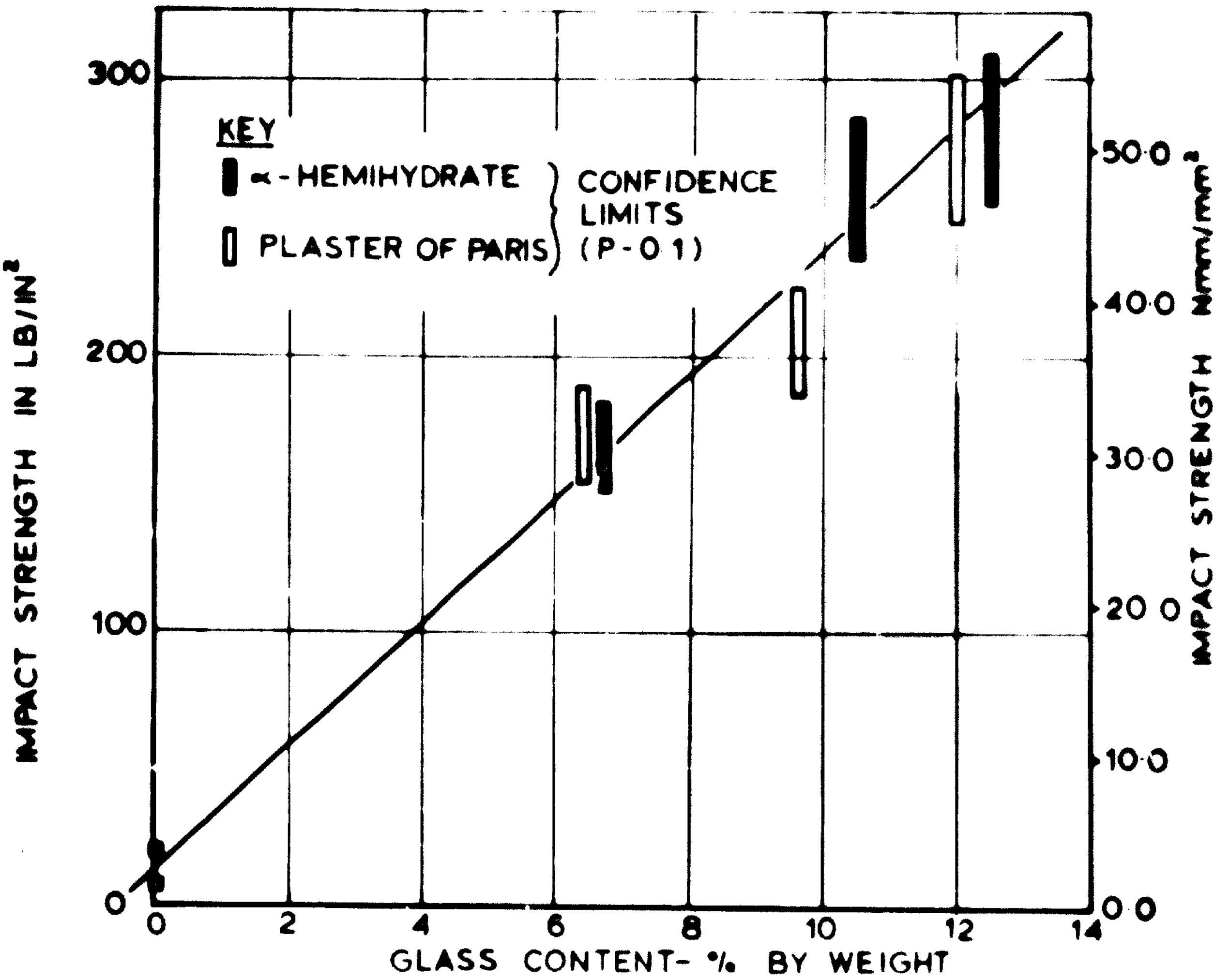


FIG. 6 RELATIONSHIP BETWEEN IMPACT STRENGTH AND GLASS CONTENT FOR GLASS FIBRE IN GYPSUM PLASTERS

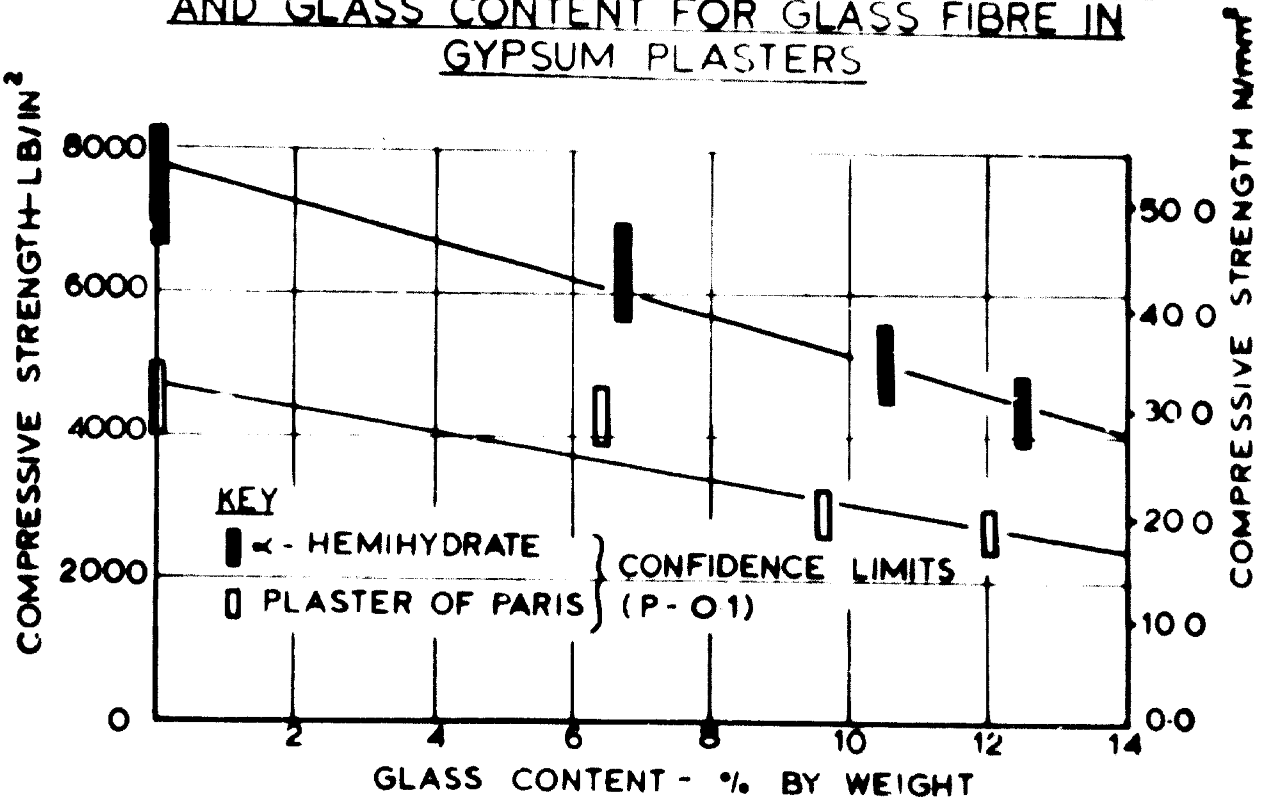


FIG. 5 RELATIONSHIP BETWEEN COMPRESSIVE STRENGTH AND GLASS CONTENT FOR GLASS FIBRE IN GYPSUM PLASTERS

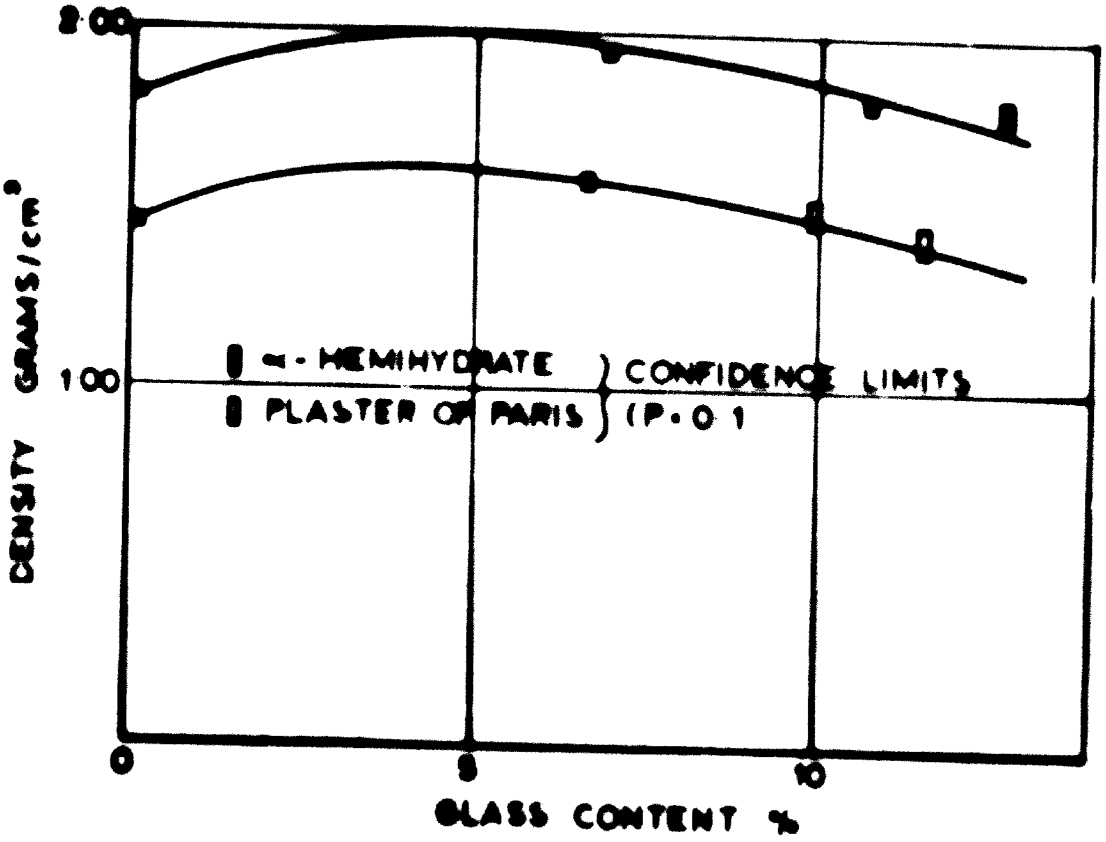


FIG. 7 RELATIONSHIP BETWEEN DENSITY AND GLASS CONTENT FOR GLASS FIBRE PLASTER COMPOSITES

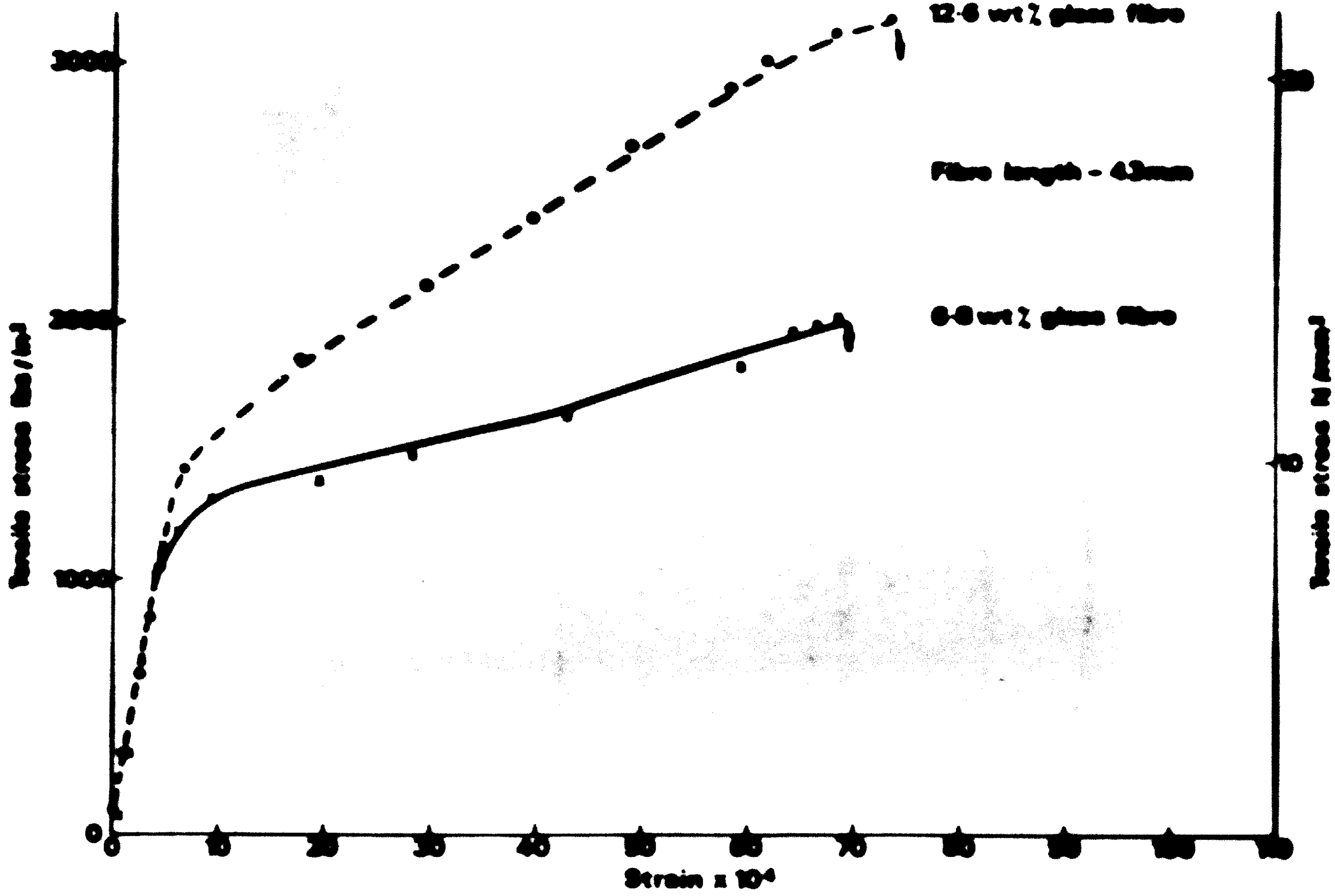


FIG.8 Stress-strain relation of GFG composite in tension

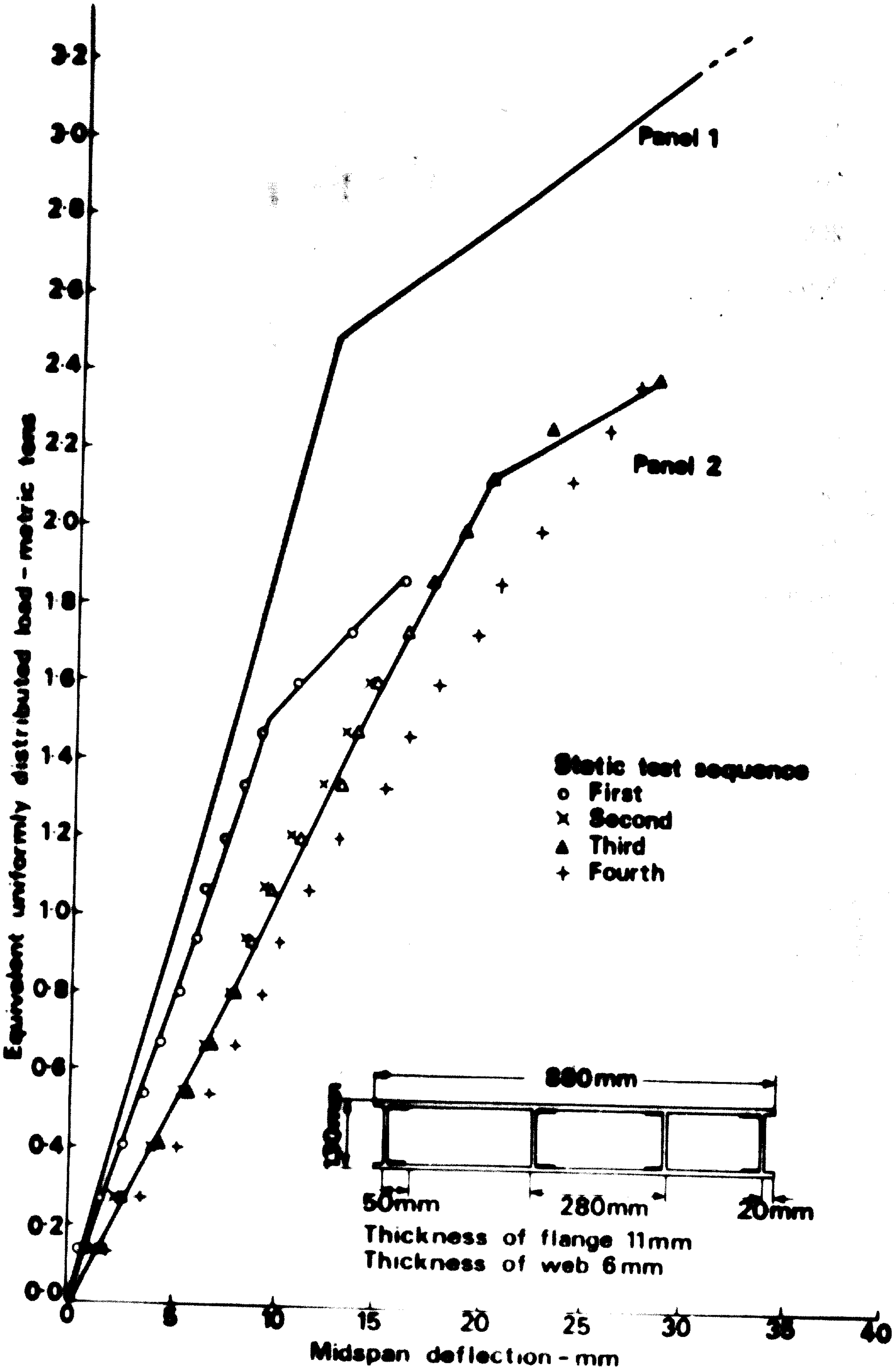


FIG.9 Load deflection curves of the floor-unit

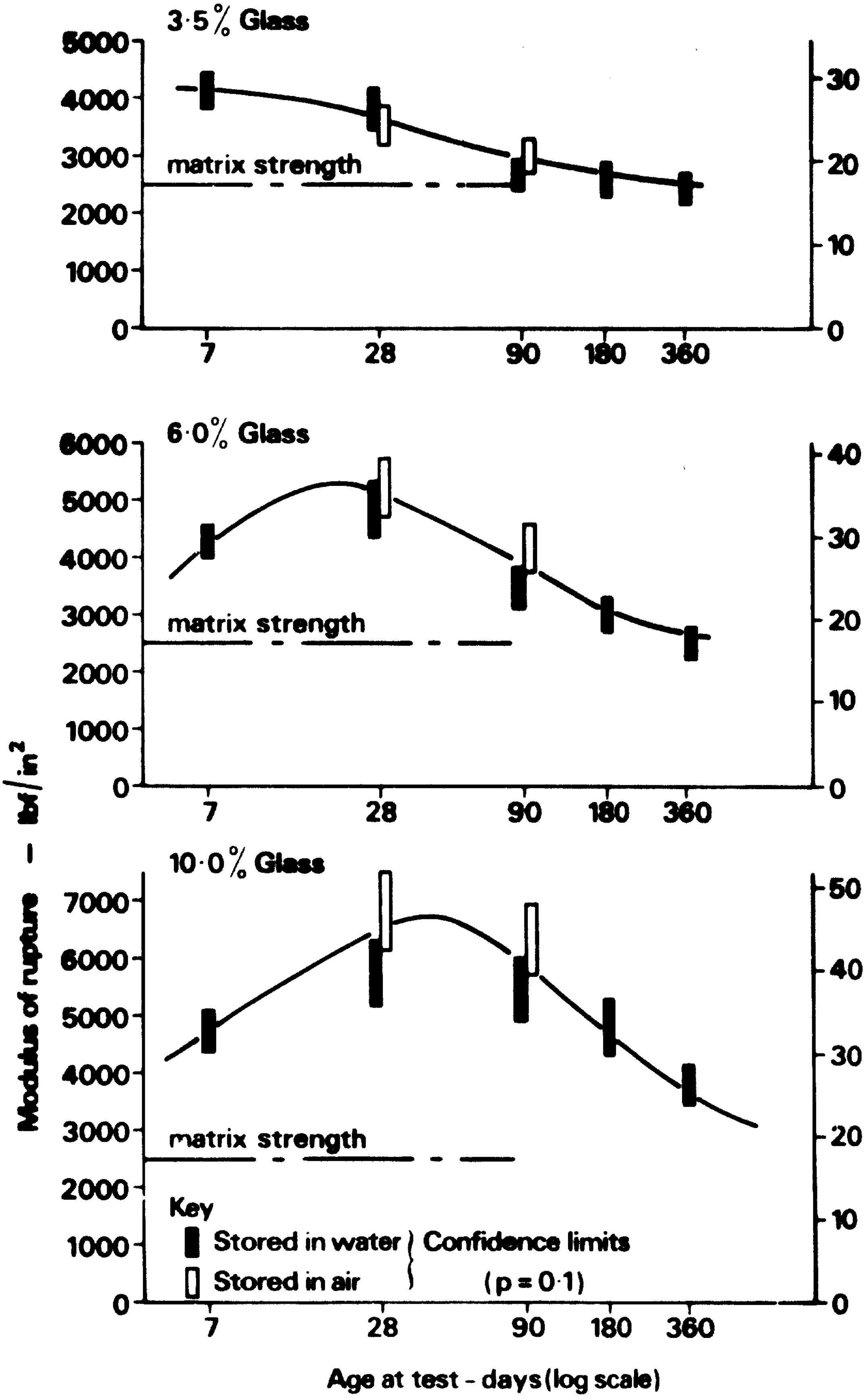


**FIG 10** Relation between modulus of rupture and age at test for glass fibre in high alumina cement matrix

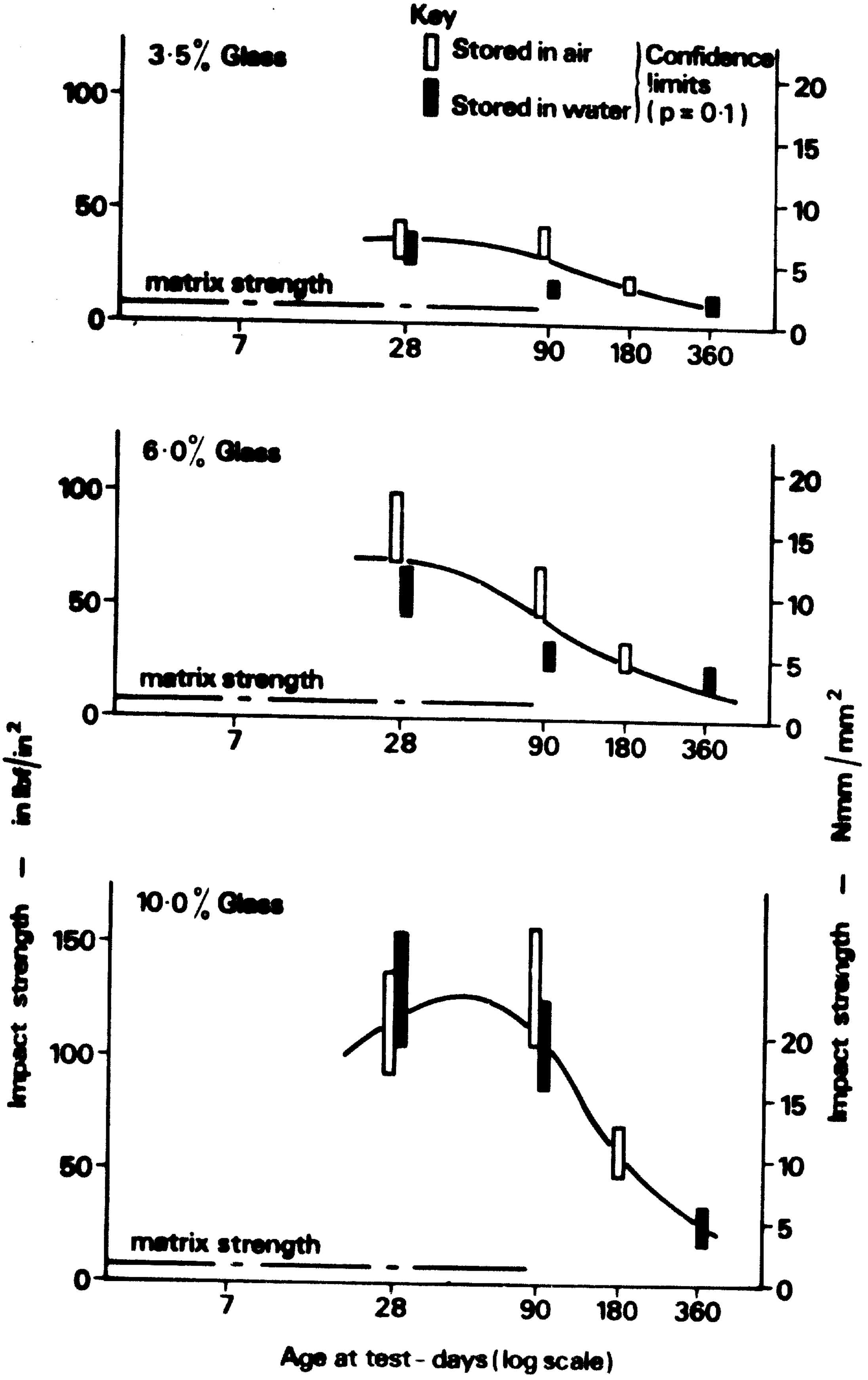


**FIG 11** Relation between impact strength and age at test for glass fibre in high alumina cement matrix

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