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Mechanical Properties of Glass Fibre-Reinforced Gypsum

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Gypsum plaster, like other inorganic cements, is strong in compression but weak in tension exhibiting brittle behaviour. Commercialy available E glass fibres can be used to reinforce the gypsum plaster matrix and produce a strong composite material having improved tensile and impact properties. This paper describes the effect of glass content on the flexural, tensile, compressive and impact strength of this glass fibre plaster composite which is made by a simple spray/suction technique.

1. Introduction

Gypsum plaster is widely used in building; mainly for coating interior surfaces. Although its compressive strength may be as high as 10 000 lb/in^2. (68.9 N/mm^2) at a low water/plaster ratio, it is comparatively weak in tension and has very low impact strength. These brittle characteristics prevent the effective utilisation of the high compressive strength in structural applications. Some improvement can be achieved by incorporating organic fibres. The large fibrous plaster-sheets, 11 mm thick, of storey height and up to 12 m long, that are extensively used in Australia as the inner leaf in framed construction, are an example of partial structural use of gypsum plaster made possible by the reinforcing effect of sisal fibres. A much greater improvement could be expected to result from the use of glass fibres as reinforcement since they are stronger than organic fibres and their much higher modulus of elasticity would allow more effective utilisation of this strength in a plaster composite. The fire resistance of such a composite will also be far superior to that of plaster reinforced with organic fibres. Preliminary findings on the possibility of reinforcing cements and plaster with glass fibres have already been reported [1, 2].

There are two main methods of reinforcing gypsum with fibrous material. One method is to concentrate the fibres in the tensile zones of the resulting structural element so as to match the external tensile force and use the matrix to match the external compressive force. As with reinforced concrete the efficiency of this process increases with increase in the reinforcement/matrix modular ratio. In the case of gypsum and glass the lower modular ratio (4 to 5) results in a relatively inefficient utilisation of the strength of glass-reinforcement.

The other method is to disperse glass fibres uniformly in the matrix so as to form a homogeneous mixture. This system, resulting in a composite material, ensures a high degree of stress distribution by the fibres and gives improved resistance to microcracking and crack propagation inside the material under service conditions. This homogeneous dispersion of the glass fibres in the matrix also ensures planar isotropy when the resulting composite material is formed into sheets. The theoretical aspects and mechanics of fibre-reinforcement have been comprehensively discussed by Kelly, Krenchel and others [3-5].

This paper reports the effects of variation of glass/plaster ratio on the mechanical properties of composites made by a simple fabrication technique.

2. Materials

2.1. Glass Fibres

Polyvinyl acetate coated rovings of E-type glass fibres were used as reinforcing material in this study. The physical properties of the glass fibres are given in table I.

TABLE I Physical and chemical properties of E-type glass fibres.

Diameter of the fibre filament	0.3 to 0.4 $\times 10^{-3}$ in. (8 to 10 μm)
Number of filaments in a strand	204
Tensile strength of the fibre	300 to 400 $\times 10^3$ lb/in.^{2} (2.06 to 2.75 $\times 10^3$ N/mm^2)
Modulus of elasticity for glass fibre	10 to 14 $\times 10^6$ lb/in.^{2} (6.89 to 7.58 $\times 10^4$ N/mm^2)
Coating on the fibres	Polyvinyl acetate

2.2 Gypsum Plaster

Among the properties desirable in the matrix phase of a composite material the following are important: grain size similar to fibre size, minimal chemical reaction with the fibres and the ability to form good interfacial bond with the fibre. Gypsum plaster is available with grain size comparable with the fibre size used in this work and being non-alkaline it is not harmful to the glass fibre. Though some research results have been published on the strength properties of cast gypsum [6], it has been only recently that De Vekey and Majumdar [7] have measured interfacial stresses between plaster and glass fibre. They show that the bond between fibre and plaster is of the same order of magnitude as between cement and steel and is dependent upon the water/plaster ratio of the plaster matrix.

Two types of commercially available hemihydrate were used for the programme: a normal plaster of Paris, i.e. β-hemihydrate, and an α-type plaster which produces a workable mix at a lower water content and hence has higher density and strength when set. Table II gives the physical and chemical properties of these two types of plaster.

TABLE II Physical and chemical properties of gypsum plaster.

	Plaster of Paris	α-type plaster
Chemical composition SO_3 content per cent	38.6	39.0
CaO content per cent	52.5	52.7
Loss on ignition at 290° C per cent	6.3	6.1
Transverse strength lb/in.^{2} (N/mm^2) (BS 1191-1967)	1040 (7.16)	1750 (12.1)

2.3 Admixtures

As the fabrication process took between $\frac{1}{2}$ and 1 h, the setting time of the plaster had to be retarded to complete the process without any loss of workability. The α-hemihydrate contained a retarder mixed in it. The plaster of Paris however required the addition of retarder and 0.1 wt. % Keratin was used to give a setting time of about 3 to 4 h. A wetting agent (Lissapol N) was added to the plaster mix to assist in wetting and dispersing the glass fibres.

3. Fabrication

The essential requirements for optimum strength are good impregnation and coating of the fibres with plaster slurry, uniform dispersion of the fibres and maximum compaction to achieve a dense material.

Two possible methods were considered. The first, a premixing technique which involved mixing of fibres and plaster slurry by normal mixing techniques, was unsuccessful as the fibres balled up around the mixer blades. The second method employed a spray technique as used in the fabrication process for glass-reinforced plastics. This technique [8], developed at the Building Research Station, uses a glass chopper mounted on a spray gun attached to a pump. Plaster slurry having a water/plaster ratio of 0.4 to 0.6 depending upon the type of plaster, is sprayed along with chopped glass fibres of 50 mm (2 in.) length onto a perforated suction mould. The mould used in the present tests was 5 ft $\times$ 3 ft (1.5 m $\times$ 1 m) and had adjustable screed boards all round so that sheets of various thickness could be made. The material was sprayed until a thickness of 10 to 13 mm ($\frac{3}{8}$ to $\frac{1}{2}$ in.) was achieved and the top surface was then levelled off with a straight edge. The excess water was then extracted by the application of suction (10 to 12 lb/in.^{2} 0.07 to 0.08 N/mm^2) for 5 min. Immediately after suction the sheet was demoulded and stored under normal indoor conditions. The glass/binder ratio was altered by controlling the number of strands chopped in a given time. It was also possible to alter the length of the chopped fibre strand by changing the number of cutting blades in the chopper drum but in the present study only 2 in. (50 mm) length fibres were used for the whole programme. After 72 h of drying in the laboratory, the sheet was sawn into the small specimens required for various tests. These specimens were stored in 40% RH at a constant temperature of 18° C

(64° F), until they were tested. The specimens were randomly allocated for various parameters using a table of random numbers to avoid any systematic variation in the sheet being confounded with the effect of the variables under investigation.

4. Testing

4.1. Flexural Strength

This was measured on specimens of 50 mm × 150 mm (2 in. × 6 in.) under four-point loading on a span of 135 mm equally divided into three parts of 45 mm each, in an Instron testing machine. Roller supports incorporating ball bearings were used to reduce friction at the supports. The load was applied through a ball and socket arrangement. A constant cross head speed of 2.5 mm/min was used for the tests. Some additional tests were also made with a tenfold increase (25.0 mm/min) and decrease (0.25 mm/min) of the cross head speed to find the effect of rate of strain on the flexural strength. The specimens were tested after ageing under the conditions specified above for periods of three weeks and six months.

In order to determine the effect of certain experimental variables, the flexural test programme was arranged as a five factor analysis. The factors investigated were:

(*a*) *Position of specimen in sheet:* Two levels; inside half remote from edge and outside half adjacent to edge.

(*b*) *Orientation of specimen in the sheet:* Two levels; parallel to longest side and perpendicular to the longest side.

(*c*) *Face stressed in tension:* Two levels; the suction surface and the free surface as fabricated.

(*d*) *Type of loading:* Two levels; three-point loading and four-point loading.

(*e*) *Strain rate:* Three levels; normal, one tenth of normal and ten times normal rate of strain.

The first three variables relate to various aspects of sheet homogeneity, the last two relate to the effect of varying the testing procedure. The specimens were allocated at random to the various treatments using a table of random numbers.

4.2. Tensile Strength

This was measured on specimens of 25 mm × 150 mm (1 in. × 6 in.) size. The specimen was clamped in the flat serrated grips of the Instron machine which had a self-aligning universal joint at the top jaw. A constant cross head speed of 2.0 mm/min was used for the test and the ultimate load recorded.

4.3. Compressive Strength

Prisms of 25 mm × 75 mm were tested for the measurement of compressive strength. The ends of the specimens were capped with neat plaster and the ultimate failure load recorded with an Instron testing machine. A constant cross head speed of 2.0 mm/min was used for all compressive strength tests.

4.4. Impact Test

A swinging pendulum Izod type impact tester was used to measure the impact strength on a 25 mm × 100 mm specimen. With the specimen clamped at the base, the pendulum was released from a constant height and its movement after the impact recorded on a calibrated scale. This reading gave the amount of energy absorbed in breaking the specimen of the particular cross-sectional area.

4.5. Density Measurement

Specimens 50 mm × 50 mm were cut from the sheet and dried at 40° C for 24 h. The dry weight was determined and then the specimens were waterproofed by applying a thin coating of grease. Their volume was then determined by weighing in water.

4.6. Stress-strain Relationship

Strain measurements were made on a specimen of size 50 mm × 150 mm (2 in. × 6 in.) in bending under four-point loading on a span of 135 mm equally divided into three parts of 45 mm each. Resistance wire type electrical strain gauges of 1 in. (25 mm) length were fixed on the compression and tensile face of the specimen in the middle third span, a zone of constant bending moment. The strains were directly recorded through a strain gauge recorder and amplifier unit onto an ultra violet recording unit. A simultaneous record of load and deflection and a strain trace in the recorder gave the stress-strain relationship to failure for the specimen.

5. Results

The modulus of rupture was calculated assuming elastic behaviour in simple bending. The relation between modulus of rupture and glass content is given in fig. 1. The corresponding graphs for tensile strength, compressive strength and impact strength are given in figs. 2, 3 and 4 respectively.

The average density was determined for each glass/binder ratio and a relation between density and glass content is given in fig. 5. The relation between modulus of rupture and rate of strain is given in fig. 6. Fig. 7 shows a typical stress-strain curve for a glass fibre α-hemihydrate composite containing about 7% glass.

All the results shown in the graphs have been presented as 90% confidence limits. The confidence limits were calculated from the formula:

$$CL = \pm \frac{t\sigma}{\sqrt{n}}$$

where t = Students t;
σ = standard deviation;
n = numbers in a sample.

The results of the five-factor analysis are given in table III. They are based on pooled results for nine sheets.

6. Discussion

From the relation between modulus of rupture and glass content (fig. 1) it is evident that the strength of the composite reached a maximum value at 7% glass content for plaster of Paris and 10% for α-hemihydrate and then fell off. This drop in strength was due to decrease in density and compressive strength of the matrix with increasing glass content, as dictated by the present fabrication technique. The maximum increase in modulus of rupture was two and a half to three times that of the plain plaster. Composites made with α-hemihydrate plaster had higher strengths than the ones made from plaster of Paris because α-hemihydrate, requiring less water for hydration, is denser and stronger than plaster of Paris.

The tensile strength versus glass content relation (fig. 2) showed the same type of behaviour except that the optimum strength was achieved at higher glass content. The increase in tensile strength expressed as the ratio of plain plaster strength was three to four times.

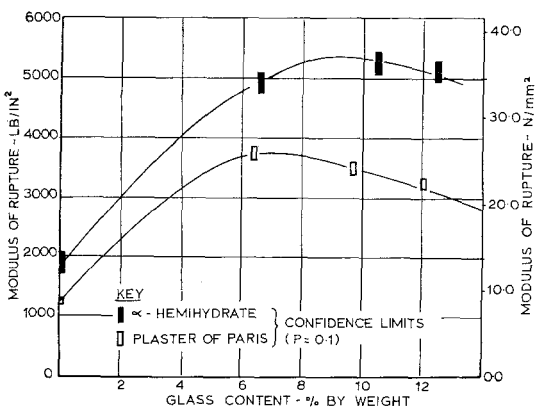

Figure 1 Relationship between modulus of rupture and glass content for glass fibres in gypsum plasters.

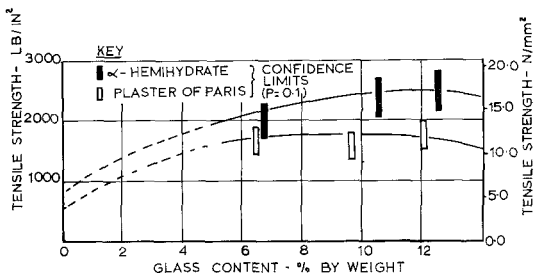

Figure 2 Relationship between tensile strength and glass content for glass fibres in gypsum plasters.

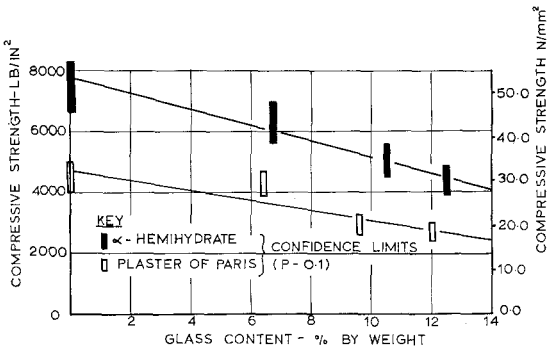

Figure 3 Relationship between compressive strength and glass content for glass fibre in gypsum plasters.

In contrast to the modulus of rupture and tensile strength, the compressive strength decreased with increasing glass content. This was due to the reduction in density of the resulting composite when made by the spray suction technique. It would be possible to obtain higher compressive strengths than the ones achieved for the same glass content if the compaction were improved by either higher suction or pressing.

The impact strength showed by far the biggest improvement with increasing glass content. The increase was twenty to thirty times the plain plaster strength for a glass content of 10 to 12%. This increase is due to the crack-arresting mechanism induced in the composite by the incorporation of fibres. The crack originating in the highly stressed tensile zones of the matrix propagates and on reaching the fibre, grows along the weak interface of the matrix and fibre. Thus the energy of the impact or fracture is

dissipated along the fibre-matrix interface and the fibres are pulled out. Pradoxically it is evident that low bond strength is an advantage as far as impact resistance is concerned.

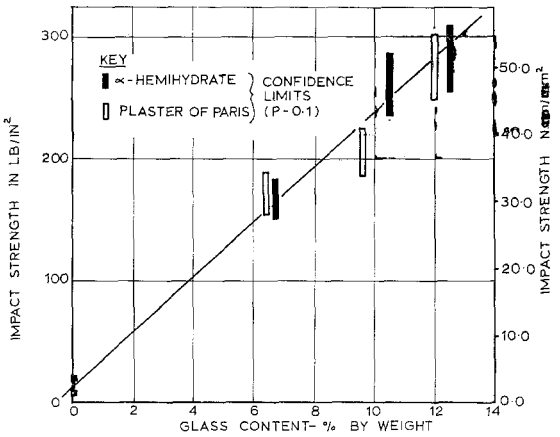

Figure 4 Relationship between impact strength and glass content for glass fibre in gypsum plasters.

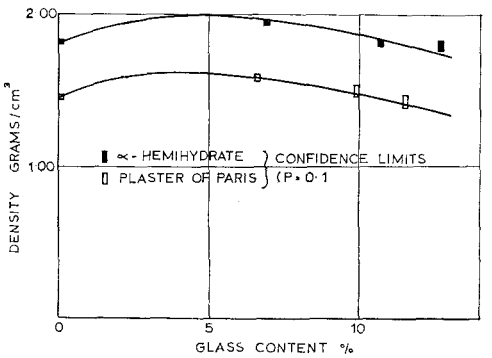

Figure 5 Relationship between density and glass content for glass fibre plaster composites.

Improvement of the bond between plaster and glass fibre by compaction will decrease the amount of crack growth along the interface and so decrease the amount of energy absorbed by this mechanism with consequent reduction in impact strength. Limited additional tests confirmed that increase in density of 10% obtained by improved compaction did in fact lead to a reduction of up to 20 to 25% in impact values.

The density versus glass content relation (fig. 5) shows a slight increase in the density at low glass content. The reason for this is obvious since glass is denser than the plaster. At higher glass content the insufficient compaction achieved by this technique induces voids in the resulting material [9]. This reduction in density is advantageous for impact strength but disadvantageous for tensile and flexural strength. It might be required to strike a compromise between these factors to achieve a product having the desired properties.

The variation in flexural strength at different rates of strain was not large enough to show any significant effect of this factor, which suggests that the creep of the material will be small.

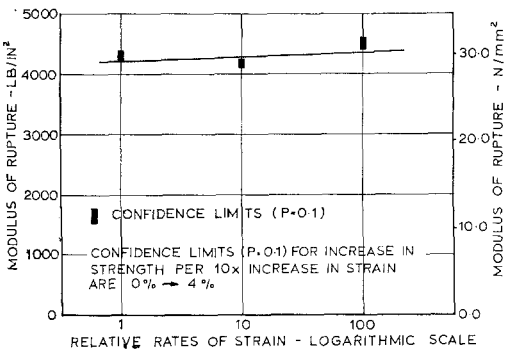

Figure 6 Relationship between modulus of rupture and rate of strain for glass fibres in gypsum plaster.

The stress-strain curves (fig. 7) indicate that at failure the glass fibre stress at the tensile face was approximately 120 000 lb/in.² (828 N/mm²), a large proportion of the fibre strength being utilised. It is not desirable to improve the matrix-fibre bond to a point where the full strength is utilised because this would result in a reduction in the fracture toughness, i.e. impact strength of the material [10]. The strain at failure on the compression face corresponded to the ultimate compressive strain for plasters.

A comparison of strengths after ageing for three weeks and six months showed that there is no significant drop in strength of the composites stored at 18° C (64° F) and 40% RH. The strength after ageing for six months was between 95 and 105% ($p = 0.1$) of the strength at three weeks.

The analysis of variance showed that only one of the homogeneity factors (factor (*c*) faces stressed in tension) and one of the testing procedure factors (factor (*d*) three-point/four-point loading) were significant. The significance of factor (*c*) showed that the sheet contained more fibres in the suction surface than in the free surface. The effect on flexure strength was

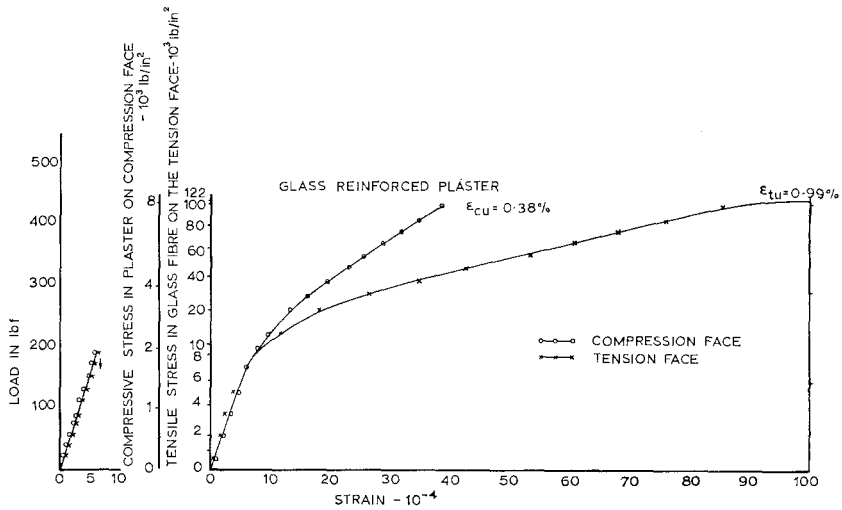

Figure 7 Stress-strain relation for plain plaster and glass-reinforced plaster in bending. Note 1 lb/in.^{2} = 6894 N/m^2; 1 lb/f = 4.448N.

TABLE III Results of five-factor analysis of variance on specimens tested in bending.

Factor code letter	Factor ratio	Confidence range for ratio ($p = 0.1$)	Significance of ratio
(*a*)	Outside/inside	0.99 to 1.02	not significant
(*b*)	Parallel to long edge/perpendicular to long edge	1.00 to 1.03	not significant
(*c*)	Tension on suction face/tension on free face	1.065 to 1.095	significant
(*d*)	Three-point/four-point	1.075 to 1.105	significant
(*e*)	Increase in strength/10 × increase in strain	1.00 to 1.04	not significant
	Residual coefficient of variation = 13 to 15% ($p = 0.1$)		

relatively small (6.5 to 9.5%) but sufficient to upset research conclusions if it is not allowed for in the design of the experiments.

The increase in strength of three-point loading compared with four-point loading can be explained as a result of the compressive stress induced in the failure zone by the central load.

It is useful to make a comparison between properties of this new material and those of ordinary asbestos cement sheet (table IV). It is clear that glass fibre-reinforced plaster is comparable with asbestos cement as regards tensile and flexural strength and greatly superior in impact strength. Its fire resistance is also very good.

7. Conclusions

1. There is sufficient interaction between glass fibres and plaster to achieve efficient reinforcement. The increase in the strength of the composites for a glass content of 10% expressed as a multiple of matrix strength was two and a

TABLE IV Comparison of structural strength of fibre-reinforced board.

	Asbestos cement sheet	Glass fibre-reinforced gypsum plaster board
Matrix	Ordinary Portland cement	Gypsum plaster
Asbestos content	10 to 15 wt %	—
Glass fibre content	—	6 to 10 wt %
Strengths		
(*a*) flexural lb/in.^{2} (N/mm^2)	4000 (28)	3500 to 5000 (24 to 35)
(*b*) tensile lb/in^2. (N/mm^2)	2000 (14)	1800 to 2500 (12 to 18)
(*c*) impact in. lb/in.^{2} (Nmm/mm^2)	10 to 15 (1.75 to 2.50)	250 to 300 (44 to 53)

half to three times for flexural and three to four times for tensile strengths.

2. It has been possible to modify the fracture mode of the gypsum plaster from brittle type to quasi-plastic type by the incorporation of the fibres. This resulted in a greatly improved impact strength which for a glass content of 10% was twenty to thirty times greater than that of unreinforced plaster.

3. There is no drop in strength of the composites made with commercially available E-type glass fibre and gypsum plaster after six months storage at 40% RH at 64° F.

4. With the present spray/suction technique the density decreased with increasing glass content resulting in lower strength of the composite. By improving the compaction technique it would be possible to achieve higher strength at high glass content.

5. The ease of manufacture combined with the excellent mechanical properties, especially high impact resistance and fire resistance, suggest that load-bearing components such as floors, partitions, inner leaf walls can be designed. Such design studies are in progress.

Acknowledgement

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