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Properties of glass fibre cement – the effect of fibre length and content

M. A. ALI, A. J. MAJUMDAR, B. SINGH
Building Research Establishment, Garston, Watford, Herts, UK

The properties of glass fibre reinforced cement composites (grc) containing alkali-resistant fibres of lengths 10 to 40 mm and volume fractions 2 to 8% have been studied. At 28 days the optimum properties of the composite were achieved with 6 vol % fibre addition. These were 4 to 5 times the bending strength, 3 to 4 times the tensile strength and 15 to 20 times the impact strength of the unreinforced cement paste. Further increase in the fibre content increases the porosity of the composite resulting in the lowering of bending and tensile strengths. The stress and strain of the composite at matrix cracking increased with increasing fibre contents. No significant improvements in the modulus of the composite were observed over the range of fibre additions investigated. The trends in the properties of grc as affected by the variations in volume fraction and length of the fibre, and environmental conditions of curing of the composites, are qualitatively related to the degree of cement hydration, changes in porosity of the composites and fibre/matrix interfacial effects. The properties of grc change with time, (strengths tend to decrease) and long term studies are in progress.

1. Introduction

The mechanical properties of a fibre composite depend very strongly on the proportion of the fibre used and its dimensions. Most of the work on glass fibre cement (grc) reported from this laboratory [1] has been carried out with composites containing 4 vol% of 34 mm long cem-FIL† alkali-resistant glass fibres arranged in an approximately two-dimensional random array. The main objective so far has been the establishment of long-term properties of such a composite. Considerable progress has been made in this direction [2] and it has now become necessary to optimize the properties of grc composites for specific uses. A study was, therefore, undertaken aimed at assessing the effect of fibre content and fibre length on grc properties. The present paper describes the 28-day results, and as the properties of grc change with time (strengths tend to decrease), long term studies are in progress.

2. Materials

A batch of ordinary Portland cement (OPC) was selected for the entire programme of work. The physical and chemical properties of this cement are listed in Table I.

The glass fibre was supplied by its manufacturer in the form of rovings having 30 strands or ends, each containing 204 individual filaments of 10 to 12 μm in diameter. The fibres were sized following the usual commercial practice.

3. Fabrication

Composite boards measuring 1.5 m × 1 m and approximately 10 mm thick were produced by the mechanised spray-suction method described elsewhere [3]. It is important to point out that this method of fabrication produces a random two-dimensional distribution of short fibres in the plane of the boards. Fibre lengths chosen for the present investigation were 10, 20, 30 and 40 mm respectively and these were easily obtained by adjusting the number of blades in the cutting roller of the glass chopper.

The fibre contents of grc boards were calculated from the quantities of cement, glass and water used in the fabrication and the weight of the demoulded board. These calculations were

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TABLE I Physical and chemical properties of ordinary Portland cement used

(a) Physical properties	
Water for standard consistency	25.3%
Setting time	(a) initial 2 h 10 min
	(b) final 3 h 30 min
Fineness	$332\,m^2\,kg^{-1}$
Soundness	2 mm expansion
Compressive strength of vibrated mortar cubes in $N\,mm^{-2}$ at:	
24 h	14
3 days	35
7 days	50
28 days	66

(b) Chemical composition	
Oxide	wt %
SiO_2	21.6
Fe_2O_3	1.84
TiO_2	0.31
P_2O_5	0.35
Mn_2O_3	0.15
Al_2O_3	4.30
CaO	65.28
MgO	1.18
Na_2O	0.15
K_2O	0.42
SO_3	3.06
Loss on ignition	1.04
Free lime	1.94

checked by weighing the quantities of glass fibre obtained by washing small areas of a green demoulded board. The calculated and measured glass contents agreed reasonably well (differences of the order of 5 to 10% were sometimes noticed).

During the fabrication, grc boards with different fibre contents and lengths, offered different resistance to the de-watering process. To achieve a reasonably constant water/cement ratio in the demoulded boards, the duration of suction and the amount of water extracted had to be controlled. Even then the final water/cement ratio of the boards in the series varies between 0.26 and 0.32.

4. Curing

24 h after demoulding, the 150 mm × 1 m strips were sprayed with water, covered with a polythene sheet and stored in the laboratory for six days. During this period the strips were sawn to give 150 mm × 50 mm test specimens. All test specimens, therefore, underwent a regime of wet curing lasting for 7 days. They were subsequently cured either in water at 18° C or in air of 40% r.h. also at 18° C. The test specimens were assigned randomly to the alternative curing conditions and pre-selected test ages to ensure that the systematic variations in the fabrication of the sheets were not confounded with the effects of the variables under investigation. The long axis of all test specimens coincided with the long axis of the board, this being the direction in which the spray-head moves in discrete steps.

5. Testing

The density of the composites was computed from the measured values of the weight and volume of the 150 mm × 50 mm test coupons which were stored in air for 21 days following the inital 7 day wet-curing.

Tensile and four-point bend tests were carried out on a Universal Instron testing machine following the procedures described previously [4]. An extensometer of 50 mm gauge length was clamped directly on the tensile test specimen for the measurement of strain. Two separate specimens were used to measure strain values corresponding to both faces and an average value was taken for constructing stress–strain diagrams. The impact strength was measured using an Izod tester of 12 J capacity.

In grc composites prepared by the spray-suction method, the location of the glass "layer" near the surface is very rarely the same for both faces. Consequently, a systematic variation in bending strengths is often observed depending on which face of the specimen is subjected to tension. Of the six specimens routinely tested in bending three were placed on the machine with their top face (as fabricated) up, the other three with top face down. The average of all six values was taken as the bending strength of the composite.

6. Results

The experimental results of the present study are plotted in Figs. 1 to 5 and 7 to 11. Fig. 6 shows two idealized tensile stress–strain graphs, corresponding to two typical grc composites. The figures are generally self-explanatory and illustrate the effect of varying the length and concentrations of glass fibre reinforcements on some of the properties of grc composites, kept in two different environments. The coefficients of variation in strength measurements of six specimens were in the range 9 to 11% for bending and tensile and 15

TABLE II Parameters used in the calculation of matrix failure strain

Symbol	Definition	Value assumed in the calculations
τ	Fibre–cement interfacial bond strength	$3\,\mathrm{MN\,m^{-2}}$
γ_m	Surface work of fracture of matrix	$10\,\mathrm{J\,m^{-2}}$
E_m	Young's modulus of cement paste	$26\,\mathrm{GN\,m^{-2}}$
E_c	Young's modulus of the composite	$30\,\mathrm{GN\,m^{-2}}$
E_f	Young's modulus of fibre	$76\,\mathrm{GN\,m^{-2}}$
V_f	Fibre volume fraction	
A_f	Effective area of the glass fibre strand	$0.027\,\mathrm{mm^2}$
P	Perimeter of glass fibre strand	1.42 mm
η	Orientation efficiency factor	

to 20% for impact strength.

In Figs. 5, 9 and 10, either the stress or the strain at the limit of proportionality (LOP) have been plotted against fibre volume percentages. The LOPs may be defined as the points where the load–deflection curve in bending or the stress–strain curve in tension deviates from linearity and they signify the termination of the elastic regime in the life of the composite under increasing load (see Fig. 6). These points are not always easy to determine by visual examination of the graphs. A reasonable accuracy is called for, however, in locating the LOP since in many instances it may mark the commencement of the cracking of the composite.

In Fig. 10 the experimental values of the matrix cracking strain have been plotted against fibre volume percentages for both air- and water-cured grc composites. According to the recent theory developed by Aveston *et al.* [5–7] for brittle-matrix composites, an increase in the failure strain of cement is to be expected from the addition of glass fibres. The basic relationship of the theory [5] needs a slight modification before they can be applied to grc as described here, to take into account the specific geometry of glass fibre strands. These reinforcements usually have a rectangular cross-section assuming the form of a tape in larger lengths. The modified expression for matrix cracking strain ϵ_{mc}:

$$\epsilon_{mc} = \left[\frac{6PT\gamma_m E_f(\eta V_f)^2}{E_c E_m^2 A_f V_m}\right]^{\frac{1}{3}}$$

has been used to predict the increase in the failure strain of the matrix. The values of the various parameters used in the calculations are given in Table II. The factor η refers to the orientation efficiency factor. Calculations depicted in Fig. 10 were carried out with three values of η, $2/\pi$, $\frac{1}{2}$ and $\frac{3}{8}$ since it is not definite yet as to which particular value is the most appropriate for the composites studied.

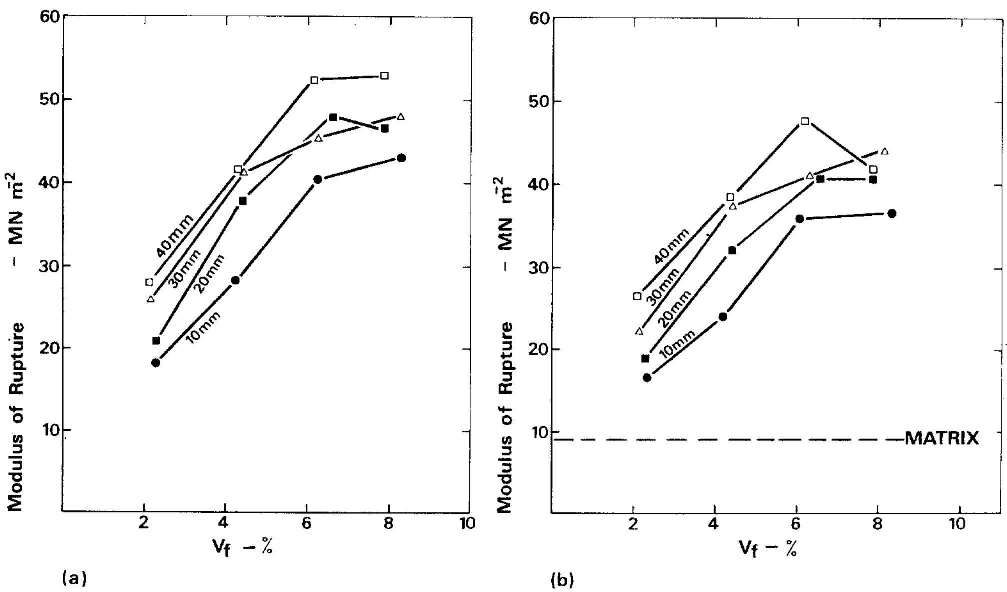

Figure 1 Relation between fibre volume fraction and modulus of rupture of grc at 28 days for different fibre lengths. (a) Stored in air, (b) stored in water.

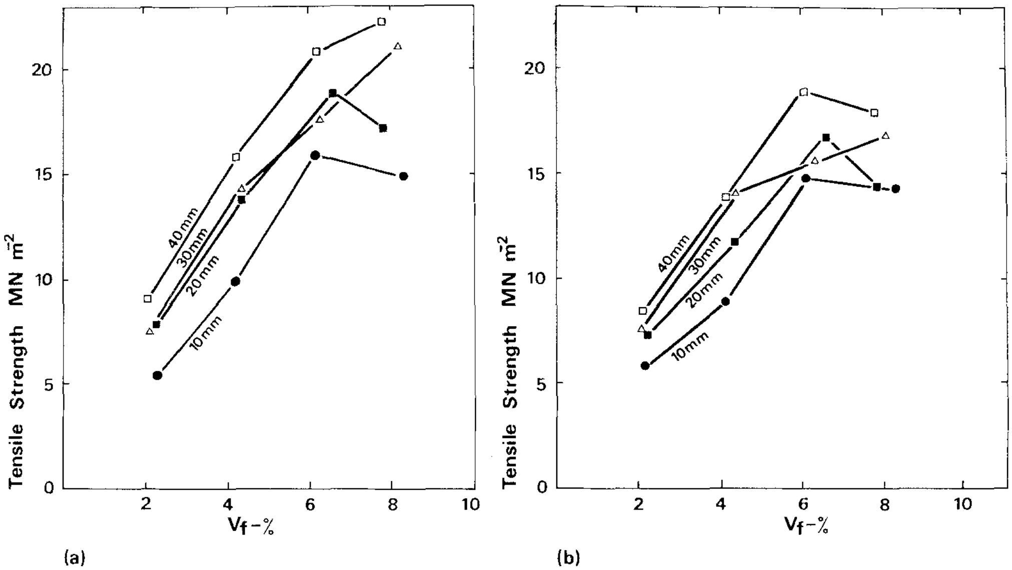

Figure 2 Relation between fibre volume fraction and tensile strength of grc at 28 days for different fibre length. (a) Stored in air, (b) stored in water.

7. Discussion of results

7.1. Strength

It is evident from Fig. 1 that for all fibre lengths used, the modulus of rupture of the composite (calculated assuming elastic behaviour) increased with increasing fibre proportions. The rate of increase in strength is quite rapid initially, extending up to about 6 vol % of fibre addition beyond which more fibres seem to have little effect. In some cases a decrease in MOR beyond 6 vol % fibre concentration has been observed. In general air-stored specimens gave slightly higher MOR values than those of the corresponding water-stored ones.

These effects of fibre additions are mirrored in the tensile strength results illustrated in Fig. 2. Again, there is an indication that for most fibre lengths, strength values reached their maxima in both environments when the fibre concentration was about 6 vol %. There is also evidence to suggest that tensile strength increases, as in the case of MOR, with increasing fibre length. This arises because the length efficiency factor for reinforcement is higher for longer fibres.

The rule of mixtures predicts that composite strengths should vary linearly with fibre volume percentages and indeed this is nearly the case in Fig. 1 and 2 up to a limiting fibre percentage of 6 vol %. Beyond this point, the porosity of the composite increases rapidly. This is clearly manifest in Fig. 3 where the density of the composite has been plotted against its fibre content. In any

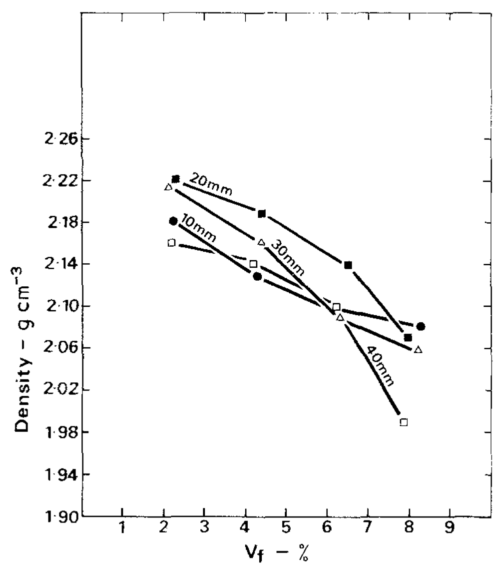

Figure 3 Relation between fibre volume fraction and density of grc composites at 28 days for different fibre lengths.

large-scale manufacturing method as has been used here it is well nigh impossible to ensure that all fabrication variables are kept under strictest control. In the manufacture of grc composites such variables are many, notably the distribution of the fibre, penetration of the fibre bundle by the matrix and the compaction of the composite. Some of the nonsystematic variations in the properties of the composite as affected by changes in fibre lengths and contents illustrated in Fig. 1 and 2 can be accounted for by the difficulties in producing fibre composites of uniform density from a particulate matrix. For such a composite there has to be an upper limit of fibre addition beyond which the reinforcing action of the fibre cannot be effectively utilized. For grc prepared by the spray suction method, this limit seems to be in the neighbourhood of 6 vol % fibre in the composite. There is also some indication that the optimum length of fibres to be used in these composites is less than 40 mm. In considering the effect of fabrication variables on the porosity of the composite it has also to be borne in mind that glass fibre strands comprising 204 individual filaments have a built-in porosity and its contribution to the total porosity of the composite is obviously dependent on both fibre content and fibre length as well as the integrity of the roving.

At the optimum level of fibre addition namely 6 vol %, the MOR values of the grc composites at 28 days were 4 to 5 times better than that of the unreinforced matrix. The corresponding improvement in tensile strength was 3 to 4 times.

The impact strength of grc composites (Fig. 4) increased with increasing fibre contents up to the limit of fibre additions (~ 8 vol %) employed in this study, in both air and water environment. The increase in the porosity of the composite resulting from fibre additions is an advantage here since it allows a reduction in the interfacial bond strength. A greater proportion of the fibre thus becomes available for pullout which, in the main, controls the work of fracture or impact strength of brittle matrix composites. The 28-day impact strength of grc having 6 vol % glass fibre is 15 to 20 times better than that of the unreinforced matrix. The impact strength seems to increase with increased fibre length, again on account of "pull-out" considerations.

In common with tensile and bending strength results, the impact strength of grc was higher in air storage than in water storage. When cured in water, cement hydrates to a greater extent than in air, the products of hydration filling the voids in the matrix as well as in the fibre strands. The overall porosity of the composite is thus reduced relative to air storage. The strands may, therefore, become less flexible, losing some of the interfilamentary friction. The impact strength of the composite is likely to decrease under these conditions.

In the air storage, the corrosive action of the cement on glass fibres is much less pronounced thereby allowing the reinforcement to retain a larger proportion of its pristine tensile strength. The strands being more flexible in air storage have a better chance of aligning themselves in the direction of stress during pull-out or elastic extensions after the multiple cracking of the matrix. Shrinkage of the cement may also produce a stronger frictional component of the interfacial bond. These factors combine to produce a high strength efficiency factor for the reinforcement

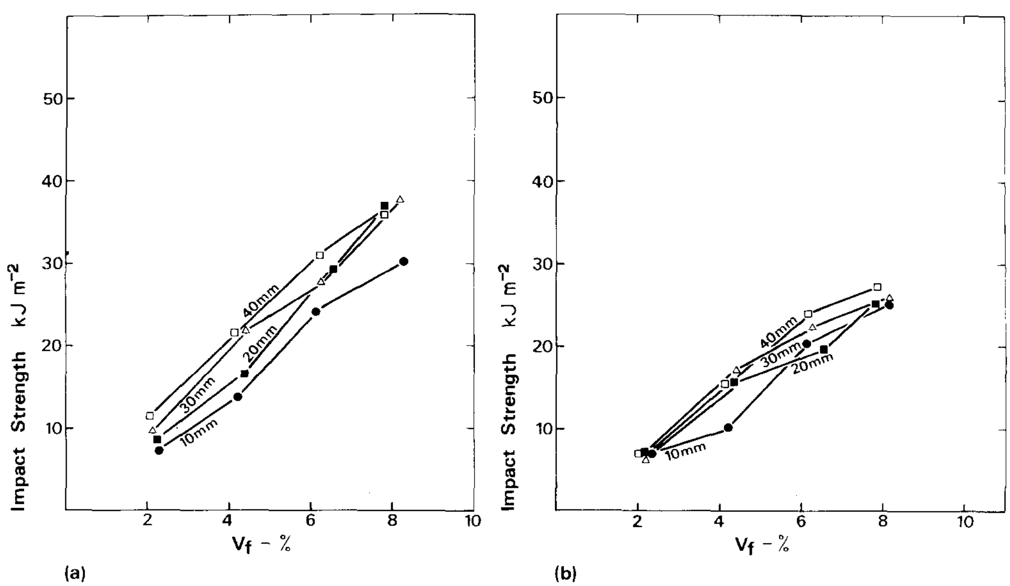

Figure 4 Relation between fibre volume fraction and impact strength of grc at 28 days. (a) Stored in air, (b) stored in water.

and consequently the MOR and tensile strength of the composite are higher in air than in water. Obviously some of these factors will have a deleterious effect on the impact strength of the composite. With present knowledge it is not possible to treat this matter in a quantitative way.

It has already been reported [2] that the strength of grc changes with time and in certain environments a decrease in strength has been noted. The effect of fibre content and fibre length on these changes in grc properties is under investigation.

7.2. Stress–strain

It is seen in Fig. 5 that the stress at the LOP in bending also reaches a maximum value around 6 vol% fibre concentration in both air and water environments. The explanation based on porosity variations advanced in the previous section applies here also. Since the composite behaves elastically up to the LOP and the fibres are strained only a

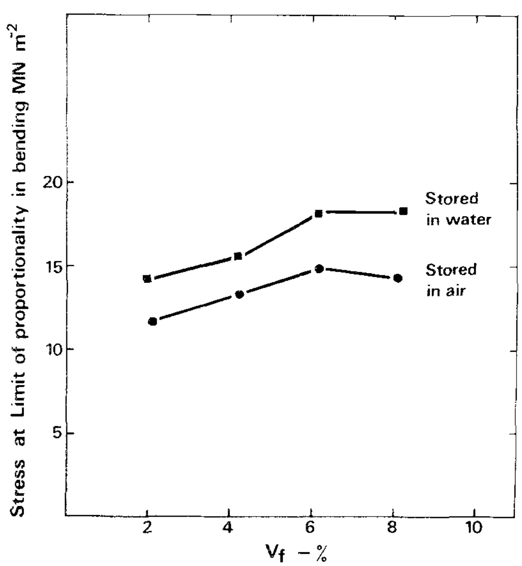

Figure 5 Relation between limit of proportionality (LOP) in bending and fibre volume fraction of grc composites at 28 days.

little because of the very low failure strain of the matrix, the contribution of the matrix to the LOP stress is the predominant factor here. Cement, when cured in water, develops a higher strength relative to air curing. This is reflected in the higher LOP stress in bending given by grc composites kept immersed in water. At 6 vol% fibre addition the stress at the LOP in bending of 28-day old composites were 30 to 50% higher than that of the unreinforced matrix.

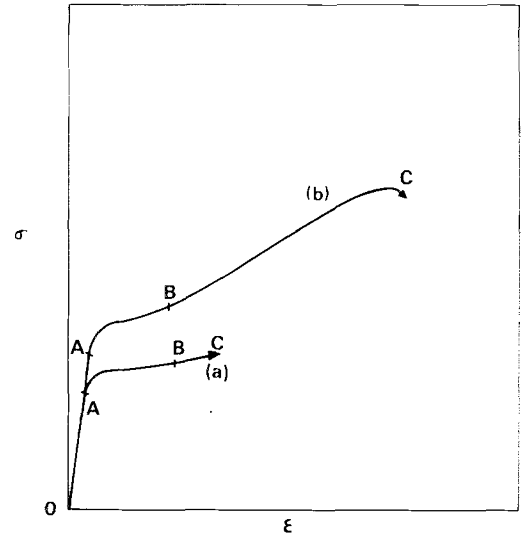

Figure 6 Idealized stress–strain curves of grc at 28 days. (a) Low fibre content of short lengths; (b) high fibre content of long lengths.

The experimental stress–strain curves in tension obtained with grc composites having various proportions of 30 mm long fibres are presented in Fig. 7, and Fig. 8 shows similar curves for 4 vol% fibre composites containing fibres of various lengths. Both set of curves also show the effect of curing conditions. In Fig. 6 two idealized stress–strain curves have been drawn for two typical combinations of fibre length and fibre content. These curves consist of three distinct regions – a linear elastic region OA terminating at the LOP where the fibre and the matrix undergo similar deformations, a region of multiple cracking of the matrix AB as described by Aveston *et al.* [5] and a final portion BC where the stress in the composite is supported by the elastic extension and pull-out of the fibres. It will be appreciated that the point on the stress–strain curve at which multiple cracking commences is almost impossible to locate as the curve bends over after the LOP.

It is seen from Fig. 7 that the increase in the stresses and strains at the LOP caused by the increase in fibre concentrations is higher in the case of water-stored samples. As mentioned before this is due to the matrix developing greater strength in water. When the proportion of the fibre in the composite is low, the stress at which multiple cracking of the matrix takes place remains constant. At higher fibre contents this stress shows an increasing trend suggesting a progressive transfer of stress across the interface. The measured strain values at the end of the

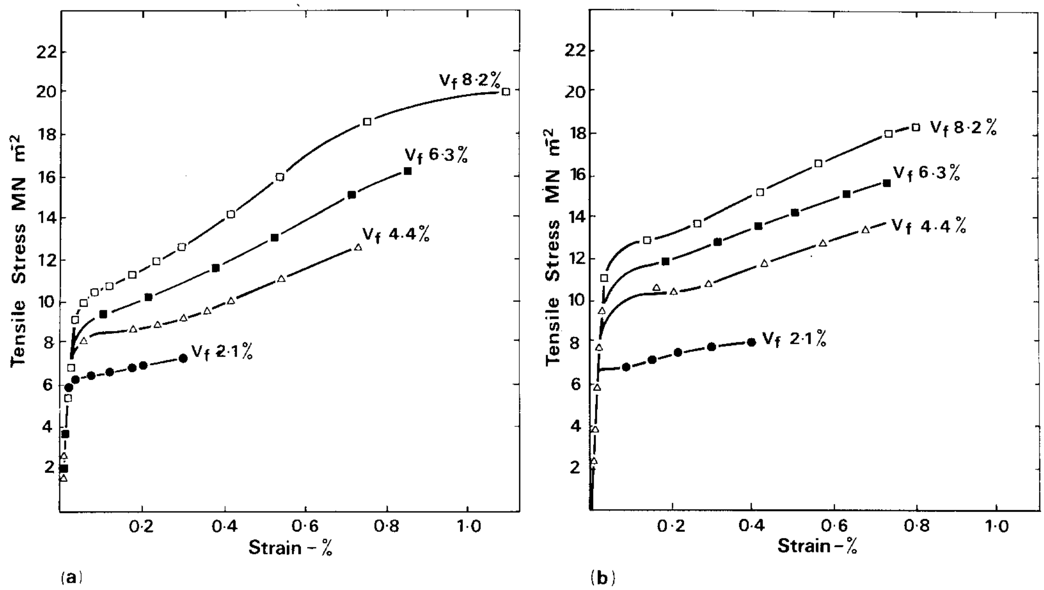

Figure 7 Tensile stress–strain curves of grc composites containing 30 mm long fibres with different fibre volume fractions of 28 days. (a) Stored in air, (b) stored in water.

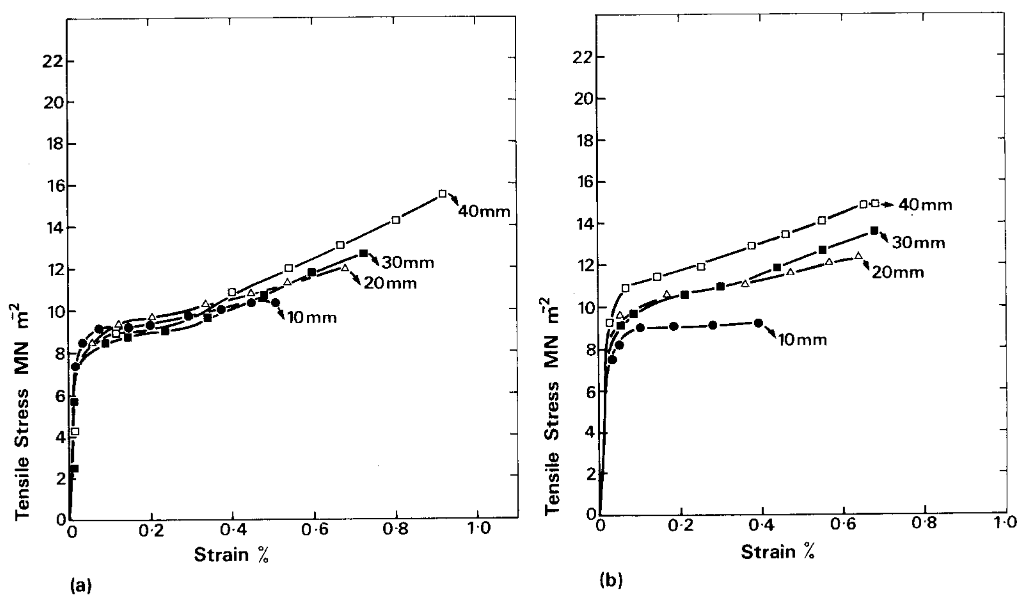

Figure 8 Tensile stress–strain curves of grc composites containing 4 vol % fibres with different fibre lengths at 28 days. (a) Stored in air, (b) stored in water.

"multiple cracking" regime showed a considerable scatter and it was not possible to judge its dependence on fibre concentrations. The slope of the third region showed an increase, as is to be expected, with increase in fibre volume percentages. The ultimate failure strain of the composite when stored in air increased from 0.3% at 2 vol % fibre addition to 1.2% at 8 vol % fibre addition.

The ultimate failure stress and strain of the composite were slightly higher in the case of grc specimens cured in air. This point has been discussed in the previous section.

The variations in fibre lengths do not influence the tensile stress–strain behaviour of grc composites nearly to the same extent as changes in the fibre content (Figs. 7 and 8). The greatest benefit brought about be the increase in fibre lengths is seen to be the improvements in the ultimate failure stress and strain of the composite.

The effect of fibre content on the cracking stress and strain of the matrix are plotted separately in Figs. 9 and 10. It has been assumed for this exercise that the cracking of the matrix begins at the LOP when the composite specimens are subjected to tension.

It is evident that the presence of fibres delays the onset of matrix cracking in proportion to the fibre content. As the properties of the cement matrix are strongly dependent on curing conditions, it is only logical to expect that the initial cracking of the composite will also be subject to the same variations. The cracking strain of the composite specimens is lower in air than water storage (Fig. 10), due to the shrinkage of the matrix. For air stored specimens, therefore, the measured cracking strain has to be corrected for shrinkage [5] in order to arrive at the true matrix cracking strain for comparison with theoretical predictions. In so far as there is positive evidence that the cracking strain of the matrix increases with fibre content, the present study supports the theory put forward by Aveston *et al.* [5–7]. However, for a random two-dimensional composite such as grc as described here, the use of the efficiency factor of $2/\pi$ or $\frac{1}{2}$ predicts a larger effect than is obtained experimentally at high glass content (Fig. 10). A factor of $\frac{3}{8}$ suggested by other workers [8, 9] brings the predicted values nearer to those reported here. A further point to consider is whether accurate theoretical predictions are possible in the present case where the composites do not have uniform porosity and variations in porosity are known to affect the properties of cement pastes markedly.

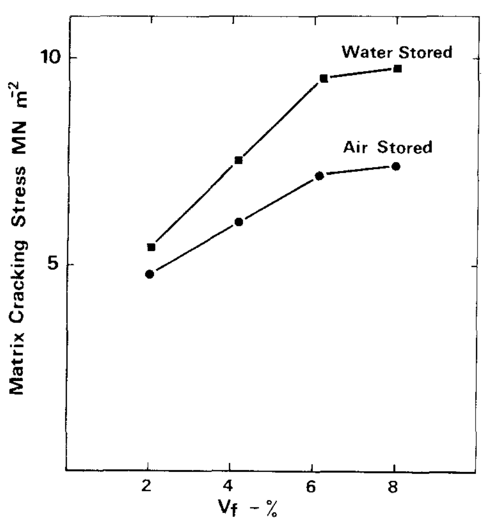

Figure 9 Relation between matrix cracking stress and fibre volume fractions for grc composites at 28 days.

The initial modulus of grc composites containing different fibre percentages as determined from their respective tensile stress strain curves are shown in Fig. 11. Since the fibre/matrix modular ratio is only 3 to 4 for grc, large changes in the modulus of the composite are not expected from the rule of mixtures when the fibre content is changed from 2 to 8 vol%. The modulus is marginally higher in water-stored samples because they are denser due to the fact that cement hydrates to a greater extent in water than in air. When the modulus of the matrix was calculated from the composite modulus values given in Fig. 11 by using the rule of mixtures, sometimes a value

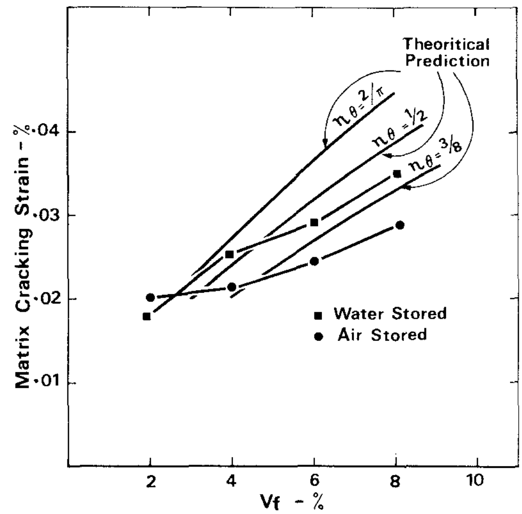

Figure 10 Relation between matrix cracking strain and fibre volume fraction for grc composites at 28 days.

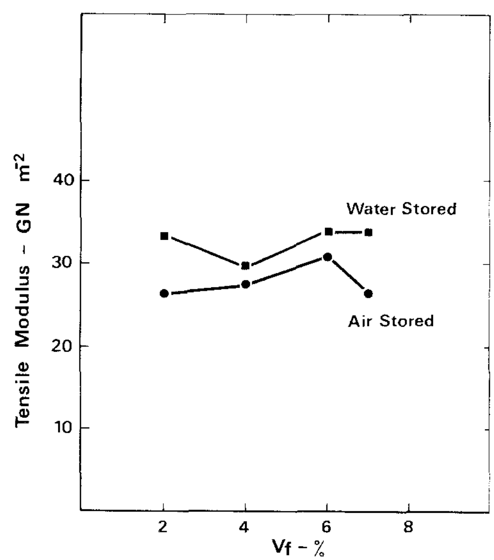

Figure 11 Relation between fibre content and tensile modulus for grc at 28 days.

larger than the measured value of the modulus of cement paste having a water to cement ratio of 0.3 was obtained. It cannot be ruled out that some of the free water was concentrated in or near the fibre bundle thereby reducing the amount of water available for cement hydration. The modulus of the matrix phase would increase under this condition.

8. Conclusions

(1) Although glass fibre concentrations of up to 10 vol% can be incorporated in a cement matrix by the spray-suction method, many of the 28-day properties of the resulting composite, notably its bending and tensile strength at the limit of proportionality and at failure attain their maximum values at 6 vol% fibre addition. These properties also show an increase with increasing fibre lengths, the rate of increase being most pronounced in the 10 to 30 mm range.

(2) The 28-day impact strength of grc composites increases with increasing fibre length and fibre content up to the limits investigated.

(3) At 28 days, grc composites containing 6 vol% of 30 mm long fibres gave 4 to 5 times the bending strength, 3 to 4 times the tensile strength and 15 to 20 times the impact strength of that of the unreinforced matrix. The failure stress and strain of the cement matrix are also considerably improved.

(4) At 28 days grc composites are slightly stronger in air than in water. However, their modulus of elasticity and stresses at the limit of proportionately are higher in water.

(5) The trends in grc properties as affected by variations in the concentration or length of the fibre and curing conditions are qualitatively relatable to (a) changes in the porosity and compaction of the composite (b) degree of cement hydration and (c) interfacial effects.

(6) It must be remembered that only 28-day values of various properties of grc given in this paper. Longer term studies are in progress; some of these show a decrease in strength properties and all results will be reported in due course.

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