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The effect of porosity on the properties of glass fibre-reinforced gypsum plaster

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The effect of porosity on the mechanical properties of composites made from brittle, particulate matrices has been studied using glass fibre-reinforced gypsum plaster as the model. Composite boards were prepared by the spray-suction method which produces a random two-dimensional arrangement of the chopped fibre in the matrix. Variation in the porosity occurred as a result of changing the proportion and length of the reinforcement. Beyond optimum fibre volume percentages, both tensile and bending strengths of the glass fibre-reinforced gypsum plaster decrease and this reduction is related to the increase in porosity which accompanies the addition of relatively large quantities of a fibrous material to a particulate matrix. The effect on porosity of a change in fibre length is less pronounced, and is only significant for lengths exceeding 22 mm. Impact strength has been found to increase with both fibre length and fibre content up to the limits that were investigated. An attempt has been made to relate the porosity of the composite (over the range 20 to 40%) with the efficiency of reinforcement by discontinuous fibres. The shape of the tensile stress–strain curve can be explained in terms of this relationship.

1. Introduction

The properties of fibre-reinforced composites depend on the strength of the fibre, the matrix and the interface between them. Brittle matrices like gypsum plaster have a high degree of porosity and hence are heterogenous in nature. The strength of the composites made from such a matrix containing short discontinuous fibres, is controlled primarily by the fibre-matrix interfacial bond and the efficiency of fibre reinforcement in improving the mechanical properties of such a material depends on the relative proportion of fibre and matrix and the way in which the fibres are dispersed in the matrix. In a previous study Ali and Grimer [1] have reported on the loss of this efficiency associated with the decreasing density of the composites caused by increasing levels of fibre addition.

In the present study, the effect of fibre content and length and their interaction on the properties of glass fibre-reinforced gypsum (grg) are examined. Mechanical strengths, stress–strain behaviour and the strength of the interfacial bond between fibre and matrix were determined experimentally at different levels of porosities. An attempt was made to relate the porosity of the composite with the efficiency of reinforcement by short discontinuous fibres and to explain its effects on the shape of the stress–strain curve of the composite.

2. Theoretical consideration

The stiffness of the fibre-reinforced composites with short discontinuous fibres in the elastic region is given by

$$E = E_m V_m + \eta_l \eta_\theta E_f V_f$$

and the stress in the composite

$$\sigma_c = \sigma_m V_m + \eta_l \eta_\theta E_f V_f \, \epsilon_c$$

where E, σ, V represent the modulus, stress and volume fraction and the subscripts m, f, c represent the matrix, fibre and the composite respectively. ϵ_c is the strain of the composite η_l and η_θ are the efficiency factors for fibre length and orientation. For composites made with a brittle matrix where $\epsilon_{mu} \ll \epsilon_{fu}$, the strength at ultimate failure is given by

$$\sigma_{cu} = \eta_l \eta_\theta \sigma_f V_f$$

where u represents the ultimate value.

The length efficiency factor, η_l, is related to the actual fibre length l_f by the relation

$$\eta_l = \left(1 - \frac{l_c}{2l_f}\right) \quad \text{provided} \quad l_f > l_c$$

where l_c, the critical length is the shortest length of the fibre which can be fractured in the composite and is given by

$$l_c = \frac{2\sigma_f A}{P\tau_b}$$

where A, P are the area and the perimeter of the fibre and τ_b the interfacial bond strength between fibre and the matrix.

The oreintation efficiency factor, η_θ, has been derived by various authors [2–5] for 2D and 3D random orientations taking into account different combinations of stress transfer mechanisms at the fibre-matrix interface, under increasing strain after multiple cracking of the matrix. These range from $2/\pi$ derived by Aveston *et al.* [6] for assumed conditions of fibre bending and alignment across a crack to $\frac{3}{8}$ for the stretching of a rigid fibrous mat across the crack [4].

The effect of the fibre volume fraction on the strength and stiffness of the composite can be predicted if the properties of the fibre, matrix and interface are known. However, for systems such as grg, where the matrix and the interface characteristics undergo a considerable change with increasing fibre content and length, due to induced porosity, these relationships have to be modified to take account of these changes.

The increase in the porosity of the matrix reduces its strength and stiffness, which alters the composite modulus and strength in the initial elastic region. It also reduces the length efficiency factor, due to a lower τ_b and hence lowers the ultimate strength and the strain at ultimate failure. Quantitative estimation of the effect of porosity on the orientation efficiency factors of short fibres has not been possible so far due to the large variability in the properties of the composites and the inaccuracies of the experimental testing technique. A factor of $\frac{3}{8}$ has been used in the predictions for the results reported here and the experimental results are in reasonable agreement with this assumption.

3. Materials

3.1. Glass fibre

Ordinary "E" glass fibres in the form of rovings containing 60 strands were used in the present programme. Each strand consisted of 204 filaments of 9.5 μm diameter and was sized with a PVA emulsion. The properties of this "E" glass strand are given in Table I.

3.2. Plaster of Paris

Commercially available fine casting plaster (Plaster of Paris) was selected for the programme. The physical and chemical properties of this plaster are given in Table I. A small percentage of Keratin was used as retarder to give a setting time of 1 to 2 h so as to allow the composite boards to be made and compacted in this period.

4. Fabrication of composites

Composite boards were produced by a spray suction technique. A 55% water content by weight slurry of plaster containing 0.05% by wt of Keratin retarder and glass fibre chopped to the correct length were sprayed together onto a perforated suction mould of size 1.5 m × 1.0 m, until a thickness of 10 mm was achieved. Excess water was extracted by the application of a suction of 0.07 to 0.08 N mm^{-2} until the material was moderately stiff but not completely dewatered. The vacuum was released and nine smaller boards measuring 275 mm × 325 mm were cut at this stage from this large board. These small boards were transferred to a mould and subsequently pressed at different compaction pressures in a hydraulic press with porous faces. Suction was also applied during the compaction process to extract the excess water. The remaining piece of board on the large mould was subjected to a further suction period of 2 to 3 min to achieve a final w/p ratio of 0.3 to 0.33. After demoulding the boards and the extracted water were weighed. The glass content and the final water to plaster ratio was estimated from the weight of the material used, the extracted water and the demoulded board.

The glass content of the board was varied by controlling the speed of the chopper, and the length of the chopped strand was altered by changing the number of cutting blades in the chopper drum. This fabrication method produced composite boards with a 2D random or planar orientation of fibres. Glass content measurements obtained by washing small areas of demoulded board showed a reasonable agreement between the measured and calculated glass content (differences of 5 to 10% were sometimes noticed). The resist-

TABLE I Physical and chemical properties of "E" glass fibres and gypsum plaster used

(a) Glass fibres:

Tensile strength of strand	Young's Modulus	Density	Poisson's ratio
1000–1400 MN m^{-2}	76 GN m^{-2}	2.54 g cm^{-3}	0.22

(b) Gypsum plaster
(i) Chemical

SO_3 content	CaO content	Loss on ignition
38.6%	52.5%	6.3%

(ii) Physical

Water: plaster ratio by wt	Porosity (%)	Flexural strength (MN m^{-2})	Tensile strength (MN m^{-2})	Modulus elasticity (GN m^{-2})	Compressive strength (MN m^{-2})
0.30	22.8	11.0	5.5	17.8	36.0
0.35	27.6	9.6	4.8	15.2	28.0
0.40	34.0	7.1	4.2	12.0	–
0.60	46.4	5.0	–	–	–

ance to suction dewatering of boards containing different fibre contents and lengths was found to vary. To achieve a reasonably constant w/p ratio in the finished boards the duration of suction and the amount of water extracted had to be controlled. Despite this the final w/p ratio of boards in the series varied between 0.3 and 0.35.

After 72 h of drying in the laboratory, the boards were sawn into 50 mm x 150 mm specimens required for various tests. These specimens were stored in air at 40% r.h. and a temperature of 18° C, until they were tested. To avoid any systematic variation in the sheet being confounded with effects of the variable under investigation, the specimens were allocated for various tests by means of a table of random numbers.

5. Interface in the composite

The "E" glass fibres used in the fabrication of the composite in the present investigations were in the form of strand, i.e. a bundle of 204 filaments. The strand shape is of a flat rectangular ribbon type and the physical dimensions of this ribbon varied considerably from strand to strand. Hardened gypsum plaster is a porous material and even though a low w/p ratio was obtained in the present fabrication technique the porosity of the finished board was as high as 20 to 30%. Thus for a bundle of fibres of variable geometry embedded in set plaster having a third of its interfacial area as voids and discontinuities, it was considered more appropriate to relate the strength of the interface to the length of the embedment of the strand rather than the area of interface. This was achieved by determining the relationship between the load required to pull out a strand and the embedded length of the strand for gypsum plaster of known porosity.

5.1. Bond strength determination

A direct method of measuring the force to pull out a single reinforcing strand embedded in gypsum plaster was used to evaluate the strength of the interface. The tests were made on the simple pull-out rig developed by de Vekey and Majumdar [7]. Specimens containing "E" glass strands of varying lengths of embedment, ranging from 2 to 15 mm, were prepared with plaster of paris having four water/plastic ratios, namely 0.35, 0.4, 0.45 and 0.5. After preparation, the specimens were stored in air at 40% r.h. and 18° C for 2 weeks and then tested on the Instron testing machine. A constant

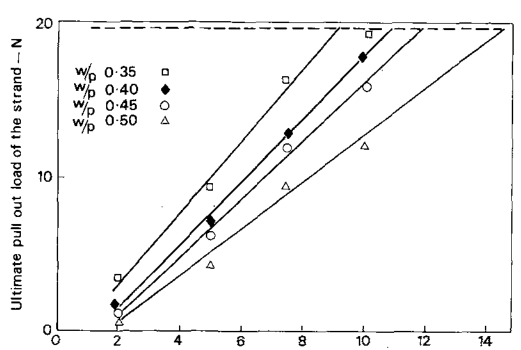

Figure 1 Relation between ultimate pull-out load and length of embedment of "E" glass strand in plaster of paris.

crosshead speed of 2 mm min^{-1} was used for the pull out tests and the load extension curve was recorded. Between ten and fifteen samples were tested for each combination of length and w/p ratio. From the test results so obtained the relationship between ultimate pull-out load and embedment length was established. This is given in Fig. 1. The average ultimate failure load of the dry strand was 19.8 N and this load formed the upper limit to the pull out process. A length of embedment that cuased a failure of strand rather than actual pull out was considered the critical length of embedment. From the relationship given in Fig. 1 and the w/p ratios used, a relationship between the porosity of the plaster and the critical length of embedment required in order to break the strand rather than pull it out was established

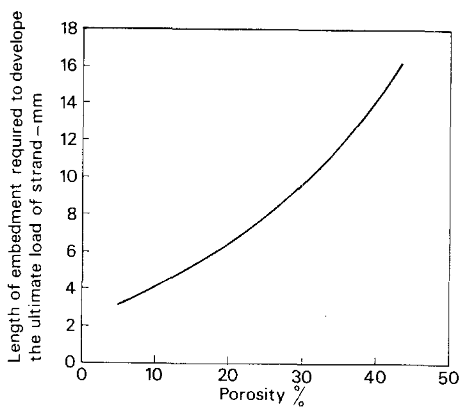

Figure 2 Relation between porosity of matrix and the critical length of embedment required to develop the ultimate load in the strand.

and is given in Fig. 2. From this relationship and the measured porosity of the composite, it was possible to obtain the critical length of the chopped fibre required in the composite, to utilise the ultimate strength of the fibre. The length efficiency factor of short discontinuous fibre can then be calculated from the relationships described earlier.

The increase or decrease of the porosity of the composite and hence of the interface, could be due to variation in water content, compaction, fibre–fibre contact, fibre length or content or to any combination of these factors. The net result of this is the variable interface which affects the efficiency of reinforcement.

6. Tests on composites

Tensile and flexural tests were carried out on an Instron testing machine following the procedures described previously [1]. The impact strength was measured on an Izod type impact tester of 12 J capacity. The density of the composites was computed from the measured weight and volume of the specimens. The strain measurements were made with an Instron extensometer of 50 mm gauge length clamped directly to the tensile test specimen. The output of the extensometer was fed via a strain gauge amplifier unit into the chart servo drive of the Instron recorder and a complete stress–strain curve up to failure of the specimen was automatically obtained.

The glass percentage by volume in the composite was calculated from the density of the composite and its glass content by weight. Porosities of the composites were derived from the volume fraction of glass and the densities of the constituents.

In grg composites made by the spray-suction technique the glass distribution achieved near the surface is rarely the same for both faces. As a result the properties observed both in tension and in bending have a systematic variation related to the particular face on which they are measured. Of the six specimens tested in bending three were tested with their top face (as fabricated) in tension and the other three with the bottom face (paper face) in tension. The average of all six specimens was taken as the mean strength of the composites. Two separate specimens were used to measure strain values corresponding to both faces and an average value was used for the stress–strain diagrams. For the Izod tests three specimens had the impact on the top face and three on the bottom face and the average of the six results was taken as the mean impact strength.

7. Results

The relations between density, porosity and fibre content of the composites for different fibre length and compaction are shown in Fig. 3. The flexural strength of the composites was calculated assuming elastic behaviour in simple bending. and its variations with fibre content is shown in Fig. 4 for two levels of porosities. The corresponding graphs for tensile and impact strength are given in Figs. 5 and 6. All the points shown in the graphs are means of six test results. The coefficient of variation of the results was about 10% for flexural and tensile strength and 20% for impact strength. Typical stress–strain relations in tension for composites containing fibre of lengths 22 and 43 mm

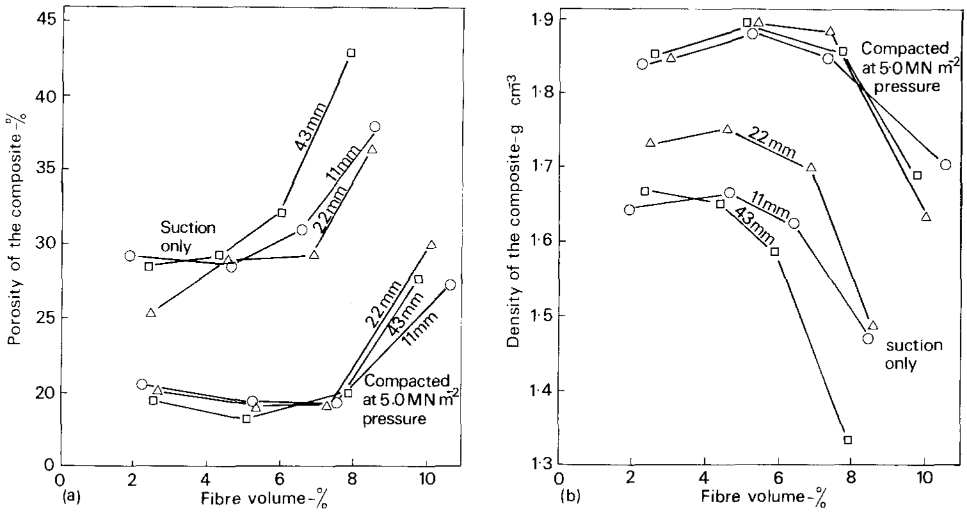

Figure 3 Relation between fibre content, porosity and density of grg composites made by spray-suction technique.

at two levels of porosity are shown in Fig. 7.

8. Discussion

The density of the composites remained stable or increased slightly initially with increasing fibre content up to a volume fraction of about 5% (Fig. 3). This is due to the higher density of glass fibre (2.54 g cm^{-3}) compared to that of set plaster (2.3 g cm^{-3}). For fibre contents higher than 5% by volume, the fibre–fibre interaction increased the porosity and hence decreased the density significantly. For the same fibre length and content better compaction increased the density and hence reduced the porosity significantly.

The effect of porosity and fibre volume fraction on the flexural and tensile strength is clearly seen in Figs. 4 and 5. The flexural strength increased with increasing fibre content up to a volume fraction of 5 to 6% as expected, so long as the porosity remained stable. Beyond this volume fraction there was a significant decrease in the strength as the porosity increased sharply, due to insufficient compaction obtained in the spray-suction method of fabrication. The optimum amount of fibre that can be efficiently incorporated without significant deterioration of strength was about 6% by volume. Additional compaction reduced this induced porosity and

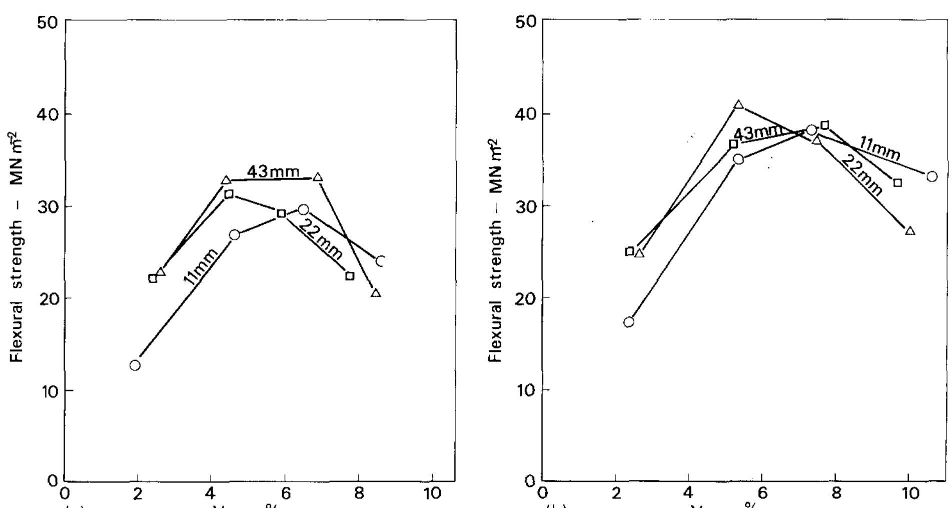

Figure 4 Relation between flexural strength and fibre content of grg composites for different fibre lengths, and made by (a) spray suction only, (b) spray suction and compacted at 5.0 MN m^{-2} pressure.

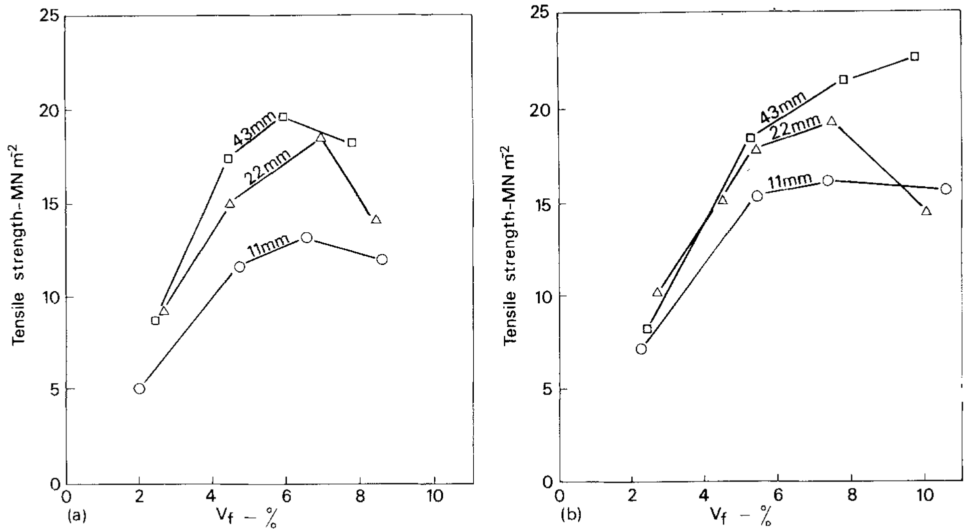

Figure 5 Relation between tensile strength and fibre content of grg composites for different fibre lengths and made by (a) spray-suction only, (b) spray-suction and compacted at 5.0 MN m^{-2} pressure.

hence increased the flexural strength for the same fibre content and length and also improved the optimum fibre addition level up to 8 vol %. This increase was partly due to an indirect increase in the fibre volume fraction of the composite and partly due to a higher length efficiency factor due to improvement in the interfacial bond.

The tensile strength of the composite also followed the same pattern as that of the flexural strength except that the optimum level of efficient fibre addition was higher than observed for flexural strength. This is due to a serious effect of porosity on the compressive strength of plaster as shown by Schiller [8, 9]. In a flexural test, the combination of compressive and tensile stresses in their respective zones controls the ultimate load sustained by the composite. At high volume fractions and hence high porosity the failure of the composite in a flexural test, though initiated by tensile cracks, was in the end due to delamination and a compression failure of the top surface. In the case of a simple tensile stress the effect of porosity was not as severe as in the complex state of stresses present in a flexure mode.

Fig. 6 shows that addition of even small amounts of glass fibres produced considerable improvements in the impact strength of gypsum plaster. Whereas plain plaster has a low impact

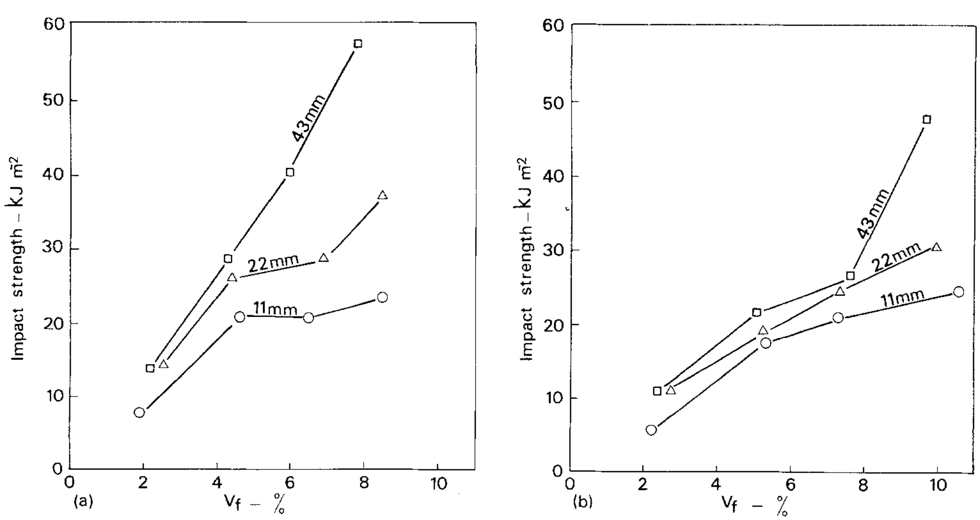

Figure 6 Relation between impact strength and fibre content of grg composites for different fibre length made by (a) spray-suction only, (b) spray-suction and compacted at 5.0 MN m^{-2} pressure.

resistance and a purely brittle behaviour, grg gave a ductile fibrous fracture under impact and the impact strength increased with increasing fibre content and length over the range investigated. The role of increased porosity in lowering the fibre–matrix interfacial bond provided a mechanism of fibre debonding and pull out under impact and hence increased the impact strength. Comparison of Fig. 6b and a shows that an increase in compaction pressure from 1 atm to $5\,MN\,m^{-2}$ increased the interfacial bond sufficiantly to increase the probability of fibre fracture rather than debonding and pull-out under impact, thus reducing the impact strength for similar fibre contents and lengths. It is worth noting that this is a paradoxical situation that greater porosity on one hand improved the impact resistance whereas on the other it significantly reduced tensile and flexural strengths. In practice a compromise has to be achieved between the various strength properties required for any specific application. Control of various parameters such as fabrication method, fibre content and length and their respective interactions normally enables a satisfactory compromise to be achieved.

There are three main effects of the porosity on the shape of the stress–strain curve of the composites as shown in Fig. 7. The first and most prominant effect is on the modulus and the stress at the elastic limit of the composite. This is as expected as these are controlled mainly by the matrix properties and both the modulus and the strength of the matrix are reduced as the porosity increases. The second effect is on the slope of the post cracking region of the stress–strain curve which is indicative of the fibre content and the length efficiency of the short fibres. An increase in the porosity of the composites containing the same fibre content and length tended to reduce the post cracking slope. Finally, the stress and strain at ultimate failure are also dependent upon the strength of the interface, which in turn depends upon the porosity of the composite.

The strength and stiffness of the composite as predicted by the relationships described earlier and corrected for the porosity effects are compared with experimental results in Table II. Considering the large number of parameters affecting the properties of individual phases, the difficulties encountered in fabrication of a homogeneous 2D random system and the inaccuracies in the experimental determination of various properties, the simple mixture law modified to take into account the porosity of the particulate system gives a reasonable agreement between the predicted and measured values of strength and stiffness of the grg composites.

9. Conclusions

For grg composite made by the normal spray-suction process, there is an increase in porosity with increasing fibre content beyond 5 vol % fibre addition. The effect of variation of fibre length on porosity is less pronounced and is only significant

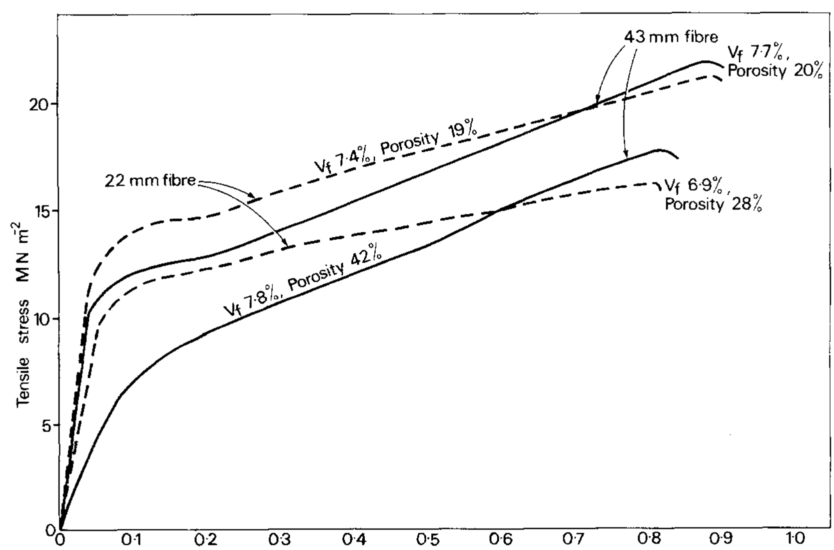

Figure 7 Stress–strain relation in tension of grg composites for two fibre lengths having different porosities.

TABLE II Calculated and measured strength and stiffness of grg composites

Compaction pressure ($MN\ m^{-2}$)	Fibre length (mm)	Fibre content by vol (%)	Porosity of composite (%)	Critical length l_c (mm)	Ultimate tensile strength of fibre ($MN\ m^{-2}$)	Young's modulus of fibre ($GN\ m^{-2}$)	Young's modulus of matrix ($GN\ m^{-2}$)	Ultimate tensile strength of composite ($MN\ m^{-2}$)		Young's modulus of the composite ($GN\ m^{-2}$)	
								Calculated	Experimental	Calculated	Experimental
Atmospheric	22	4.39	28.32	17.6	1100	76	14.7	10.90	15.00	15.30	17.80
	22	6.90	28.70	18.0	1100	76	14.6	16.85	16.55	15.60	20.00
	22	8.45	36.30	24.4	1100	76	11.5	15.70	14.10	12.90	10.00
	43	4.33	28.49	17.8	950	76	14.8	12.20	17.40	15.30	16.40
	43	5.94	31.44	20.2	950	76	13.4	16.25	19.60	14.30	16.00
	43	7.80	42.42	32.0	950	76	9.2	18.00	18.10	10.70	8.00
5.0	22	5.32	18.39	12.2	1100	76	20.6	15.90	17.80	21.00	25.00
	22	7.39	19.10	12.6	1100	76	20.2	21.80	19.40	20.80	26.00
	22	9.98	30.00	19.2	1100	76	14.2	23.60	18.60	15.60	10.00
	43	5.08	18.02	11.8	950	76	20.8	15.85	18.35	21.20	19.40
	43	7.73	19.86	13.0	950	76	19.8	23.40	21.30	20.50	19.00
	43	9.58	27.53	17.2	950	76	15.3	27.60	22.70	16.50	10.00

for lengths exceeding 22 mm. The fibre volume fraction that can be efficiently incorporated to achieve optimum flexural strength was 5 to 6%, whereas the optimum tensile strength was achieved at 6 to 8 vol % fibre addition. When compaction pressured was used to achieve a lower porosity the volume fraction to obtain maximum flexural and tensile strength was increased. The strengths achieved were also higher than those obtained with an uncompacted material. The flexural and tensile strength of the composites increased with increasing content of fibre of a constant length as well as with increasing fibre length for the same volume fraction so long as the interface properties remained constant. Significant increase in porosity affected the length efficiency of the short fibrous reinforcement and the composite strengths decreased. Impact strengths increased with increasing fibre length and content, and with porosity upto the maximum of 10 vol % fibre addition that was studied. The shape of the stress–strain curves can be qualitatively explained in terms of the various effects of porosity on matrix strength and stiffness and the interfacial bond.

These conclusions are relevant to the practical applications of grg by firms licensed by the NRDC to use patented processes developed by the Building Research Establishment.

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