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The durability of glass fibre cement – the effect of fibre length and content

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The properties of glass reinforced cement composites (grc) containing 2–8 vol % of alkali resistant glass fibres of lengths 10–40 mm have been studied for periods of up to 5 years in various environments. Fibre volume fraction was found to be an important factor influencing the strength of grc at all ages, while fibre length was of decreasing significance as storage periods in wet environments increased. In relatively dry conditions, little change with time of bending, tensile or impact strengths was observed, but the matrix cracking stress was reduced. In wet environments, the cracking stress tended to increase but the ultimate strength to decrease.

At 28 days maximum strength was achieved with composites having 6 to 8 vol % fibre 30 to 40 mm long. Composites with similar formulations were found to have the greater strength after 5 years' storage but, after water storage or natural weathering a strength reduction had occurred. Bending strength was approximately 70% to 86% of its 28 day value, tensile strength between 55% and 84% and impact strength 32% to 78%. Young's modulus is largely dependent upon the degree of hydration of the cement matrix and in the long-term was greater for water-stored material than for that stored in dry air.

1. Introduction

In the last few years the use of glass reinforced cement (grc) in non-load bearing applications in the construction industry has widened considerably [1, 2]. These applications are based, in the main, on the projected long-term properties of the grc composite made from ordinary Portland cement (OPC) and containing 4 vol % of 34 to 38 mm long Cem–FIL* alkali-resistant glass fibres in two-dimensional random orientation [3]. Some guidelines regarding the probable application areas for this new material have also been given [4].

In a comprehensive programme aimed at determining the effect of composition variables on the long-term properties of grc, the influence of fibre length and fibre content is being studied. The 28-day results on the properties of grc composites containing different proportions of fibres of varying lengths and kept in dry and wet environments have already been described [5]. The present paper considers the 5-year results.

2. Materials, fabrication and curing

The grc composites were prepared from OPC and Cem–FIL AR glass fibre rovings in the form of 1.5 m × 1 m boards, approximately 10 mm thick by the spray-suction method described previously [6]. The boards were cut with a knife in the green state to provide 150 mm × 1 m strips which were sprayed with water 24 h after demoulding, covered with a polythene sheet and stored in the laboratory in a damp condition for 6 days. During this period the strips were sawn to give 150 mm × 50 mm test specimens, their long axis coinciding with the long axis of the boards. All test specimens, therefore, underwent a regime of wet curing lasting 7 days. They were then distributed randomly and kept in three different environments: (a) in air at 18 to 20° C, 40% r.h., (b) in water at 18 to 20° C, and (c) on the weathering site at Garston.

3. Testing

The mechanical properties of the composites were determined as pre-selected ages. Tests were

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normally carried out at 7, 28, 90, 180 and 365 days after the composite boards were manufactured and at yearly intervals thereafter, Although a very large proportion of specimens has already been used up, there are some remaining and it is intended that these will be tested at 10 years.

The tensile, bending and impact properties were measured routinely using procedures described elsewhere [7]. 150 mm x 50 mm specimens were broken in four-point bending and direct tension using an Instron testing machine and for impact strength an Izod type instrument was employed.

4. Results

The effect of fibre length and content on the long-term properties of grc has been studied for fibres 10, 20, 30 and 40 mm long and at four levels of fibre additions: approximately 2, 4, 6 and 8 vol%. The test programme has necessarily generated an enormous amount of data; for economy of space only the essential data are presented here.

The effect of varying fibre proportions on the MOR (modulus of rupture calculated from the elastic beam theory) of grc is illustrated in Figs. 1 to 3 by the results obtained with composites containing 30 mm long fibres. The experimental values are averages of six results (C V 10% to 13%); those obtained after 1 year and 5 years are listed in Table I. Table II compares the grc strength values obtained after 5 years with those after 28 days. It should be noted here that the first set of weathering results was obtained with specimens that had undergone 6 months' exposure to natural conditions outdoors and in comparisons with initial values (for instance in Table II) results obtained with air and/or water stored samples have been used.

Tensile and impact strengths follow a generally similar ageing pattern to the MOR and are listed in Tables I and II (C V 8% to 13% and 13% to 18% for tensile and impact strength respectively). The effect of fibre proportions on the limit of proportionality (LOP) in bending and on the stress and strain values corresponding to matrix cracking in tension is illustrated in Figs. 4 and 5 for the three environments studied. For these diagrams the results obtained with different fibre lengths have been averaged. Some idea of the effect of fibre length on these properties of grc can be obtained from Table IV. Fig. 6 shows the effect

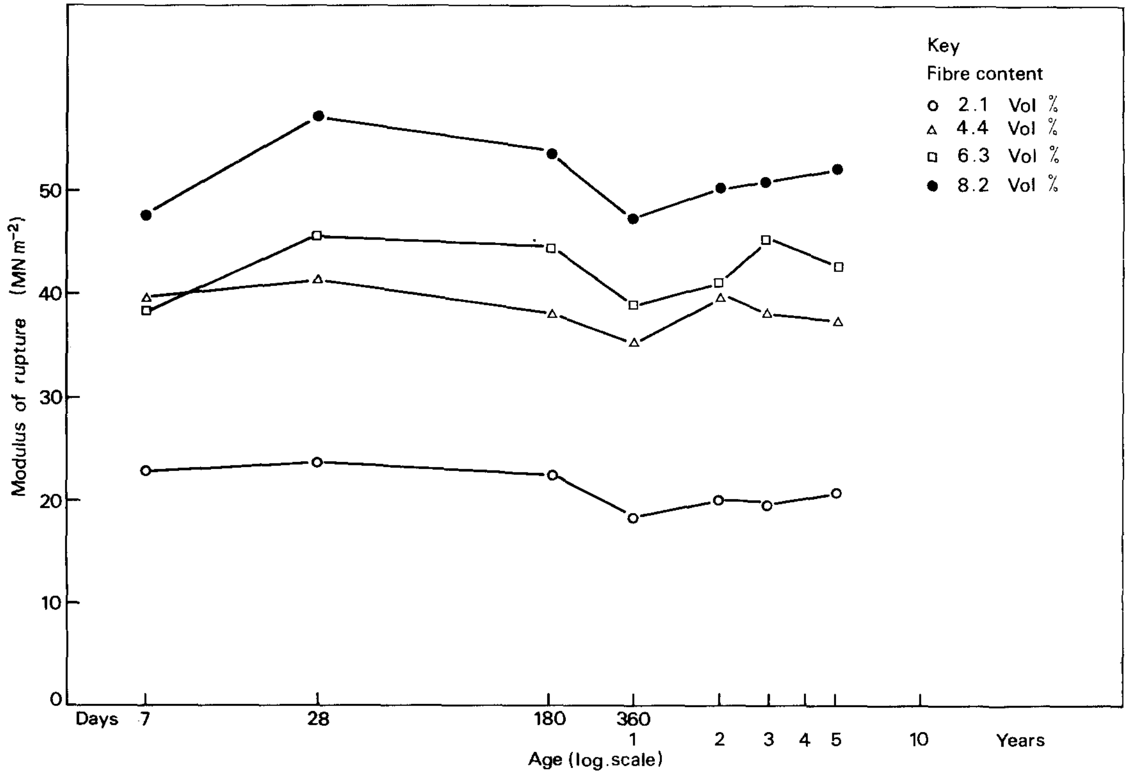

Figure 1 Bending strength of grc stored in air at various ages. Fibre length 30 mm.

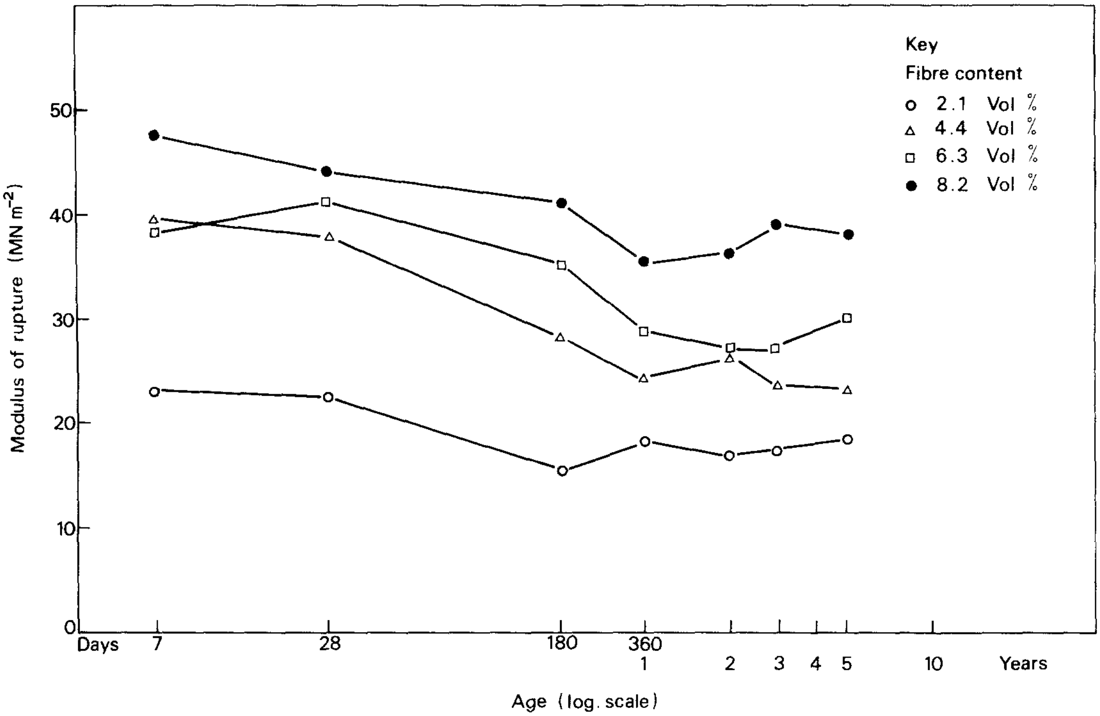

Figure 2 Bending strength of grc stored in water at various ages. Fibre length 30 mm.

of time and environmental conditions on the matrix cracking strain. At each fibre level the strain values plotted are averages of all fibre lengths studied.

The tensile stress–strain diagrams obtained with 5-year-old composites containing 4.4 and 8.2 vol% of 40 mm long fibres are shown in Fig. 7. The effect of age and environment on the ultimate

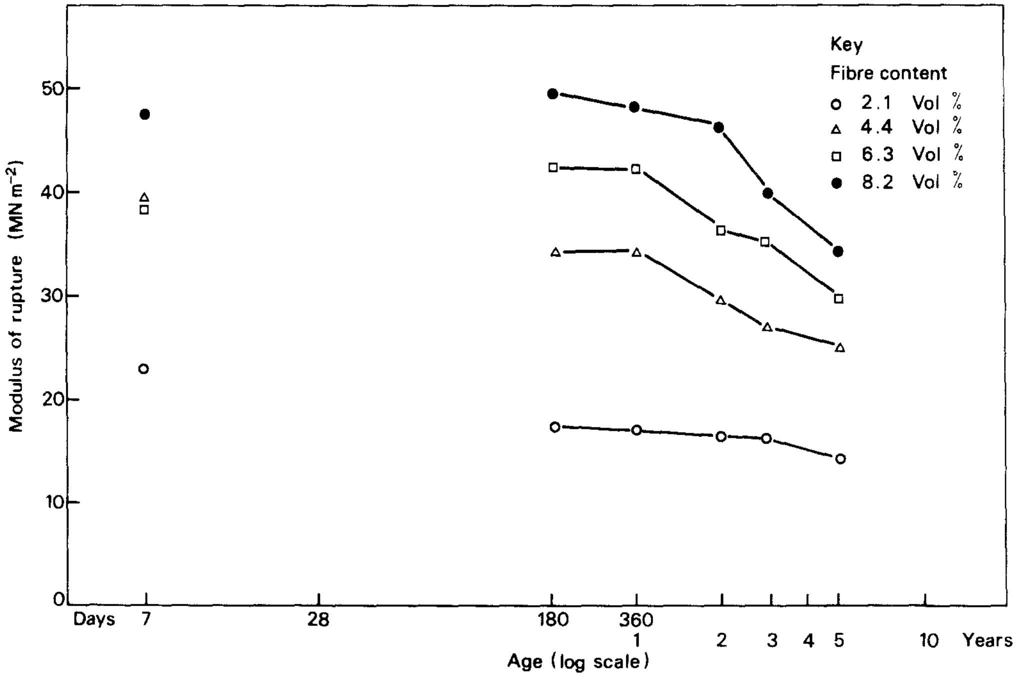

Figure 3 Bending strength of grc in natural weathering conditions at various ages. Fibre length 30 mm.

TABLE I MOR, UTS and impact strength of grc composites at 1 year and 5 years for varying glass contents and glass lengths

Glass		1 year								
Content (vol %)	Length (mm)	MOR ($\mathrm{MN\,m^{-2}}$)			UTS ($\mathrm{MN\,m^{-2}}$)			I.S. ($\mathrm{KJ\,m^{-2}}$)		
		Air	Water	Weather	Air	Water	Weather	Air	Water	Weather
2.1	10	14.0	15.2	13.8	9.0	6.7	7.5	8.0	3.0	6.0
	20	18.3	15.0	15.4	6.6	5.7	6.4	9.2	4.2	7.4
	30	18.3	18.2	17.0	6.9	5.8	6.4	10.2	5.8	7.0
	40	22.5	14.4	18.9	8.0	6.3	7.3	11.2	4.0	8.3
4.4	10	25.5	19.4	25.0	12.2	10.8	8.8	16.6	7.0	10.6
	20	33.9	22.3	32.8	12.1	8.5	11.3	20.4	8.7	16.3
	30	35.4	24.3	34.5	13.8	8.8	11.8	23.2	8.3	16.8
	40	39.0	22.5	35.2	14.7	9.7	11.7	23.4	9.6	16.5
6.3	10	33.2	27.7	33.8	13.6	11.2	13.4	22.0	12.7	16.5
	20	42.4	29.0	41.3	16.0	13.2	16.6	30.0	13.3	24.8
	30	38.9	29.0	42.5	16.2	11.6	15.7	24.6	13.6	17.0
	40	49.7	32.0	47.0	20.6	13.8	17.0	38.8	18.2	25.7
8.2	10	40.0	32.2	38.4	15.0	13.3	16.0	33.3	21.1	20.3
	20	40.5	30.6	41.2	14.0	12.7	14.2	40.5	18.4	33.8
	30	47.7	35.6	48.2	18.8	15.8	19.0	31.0	21.8	27.6
	40	48.9	32.5	47.0	20.5	13.5	17.8	46.0	21.6	34.7

Glass		5 years								
Content (vol %)	Length (mm)	MOR ($\mathrm{MN\,m^{-2}}$)			UTS ($\mathrm{MN\,m^{-2}}$)			I.S. ($\mathrm{KJ\,m^{-2}}$)		
		Air	Water	Weather	Air	Water	Weather	Air	Water	Weather
2.1	10	15.0	15.0	12.0	5.3	3.8	4.0	6.2	3.8	4.8
	20	16.8	15.6	12.0	6.0	3.5	4.3	9.0	3.0	5.0
	30	20.8	18.5	14.2	5.6	4.3	3.5	11.2	3.3	4.7
	40	21.5	15.4	14.5	6.5	3.7	5.6	10.4	3.5	5.6
4.4	10	25.4	20.5	20.5	8.2	6.0	6.5	14.6	4.0	6.0
	20	32.0	22.6	25.0	11.7	6.5	8.0	17.8	4.5	8.0
	30	37.4	23.5	25.0	12.7	8.0	8.5	20.6	5.0	7.8
	40	38.3	24.7	24.8	13.7	7.5	8.6	21.4	4.7	8.3
6.3	10	33.0	27.7	30.0	12.2	9.3	10.0	20.7	6.0	10.0
	20	44.0	30.5	34.2	16.2	12.3	10.6	27.2	6.2	16.5
	30	43.0	30.3	29.8	15.7	10.3	8.6	26.4	7.6	17.7
	40	51.8	34.0	36.2	17.3	12.3	10.7	37.8	7.7	10.0
8.2	10	42.5	34.7	35.4	15.2	12.4	13.0	34.8	11.8	16.4
	20	39.0	30.0	35.3	12.5	11.4	11.0	40.2	12.6	21.7
	30	52.2	38.0	34.4	18.0	14.3	10.6	43.5	13.6	15.0
	40	49.7	32.0	34.6	18.3	11.6	11.5	40.0	12.3	16.0

failure strain of grc composites is illustrated in Fig. 8 and their MOR/UTS (ultimate tensile strength) in Fig. 9. The corresponding Young's modulus values averaged over all fibre lengths have been plotted in Fig. 10.

To assess the effect of temperature and humidity on composite properties, grc specimens were kept in an oven at 40° C (in laboratory air, without humidity control) for a prolonged period. They were also stored in a room where the temperature and humidity were maintained at 20° C and 90% r.h. The strength results from these specimens are given in Table III. Some specimens were also subjected to accelerated ageing under water at 60° C.

5. Discussion

5.1. Strength

As with other composite materials, the properties of grc are governed by, among other factors, the fabrication variables in its manufacturing process. Experience has shown that the spray-suction

TABLE II Grc strength at 5 years relative to 28 day values (%)

Glass		Modulus of rupture			Tensile strength			Impact strength		
Content (vol %)	Length (mm)	Air	Water	Natural weathering	Air	Water	Natural weathering	Air	Water	Natural weathering
2.1	10	83	88	70	98	64	66	83	52	66
	20	79	82	63	76	47	58	101	43	71
	30	88	83	63	76	57	46	114	53	76
	40	78	58	55	72	45	66	90	51	81
4.4	10	90	85	85	82	68	74	104	39	57
	20	84	70	77	84	55	68	105	28	50
	30	90	62	66	89	57	60	94	29	45
	40	92	65	66	86	54	62	97	31	54
6.3	10	80	76	82	76	62	66	84	29	48
	20	93	75	84	85	73	63	91	31	82
	30	94	74	72	90	66	55	95	33	78
	40	98	70	75	83	64	56	120	32	42
8.2	10	99	94	96	102	86	90	114	44	61
	20	82	89	105	74	81	78	85	49	84
	30	92	86	78	84	84	62	114	51	57
	40	94	77	83	82	64	64	111	45	59

method employed in the production of composite boards used in the present study does not produce a completely uniform material. Longitudinal specimens are slightly stronger than transverse ones but the variability from this source can be eliminated by choosing a fixed orientation (for the test specimens) with respect to the axes of the board. In the present study only longitudinal specimens have been tested. In addition, a systematic variation in flexural properties is observed depending on which face of the specimen is subjected to tension in the bending test. To accommodate this "top and bottom effect", six specimens are tested in bending – three with their top face (as manufactured) in tension and three with the bottom face in tension – and the average taken as the bending strength of the composite.

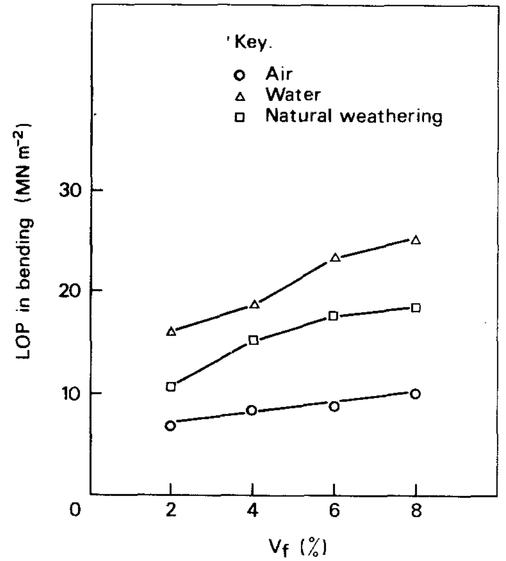

Figure 4 Relation between the limit of proportionality in beinding and the fibre volume fraction at age 5 years.

From an examination of Figs. 1 to 3 it can be seen that the strength of grc is influenced by age and storage conditions. Impact, tensile and flexural strength tend to decrease after extended periods of water storage or natural weathering but the initial strength is largely retained during similar periods of storage in dry air (Table II). These results are in general agreement with an earlier study, conducted over 5 years, on grc containing ~ 4 vol% glass [3].

In addition the present study examines the influence of glass content and fibre length on the properties of grc. Figs. 1 to 3 suggest that composites having the higher fibre contents are initially the stronger and that this effect is maintained throughout all ages and storage regimes considered. To confirm this effect and also to investigate the influence of other factors on the strength properties (over the range of storage conditions up to 5 years) a statistical analysis of the data was undertaken.

A two-way analysis of variance technique was employed to determine the significance of the effects of fibre volume fraction and fibre length on the impact and tensile strengths.

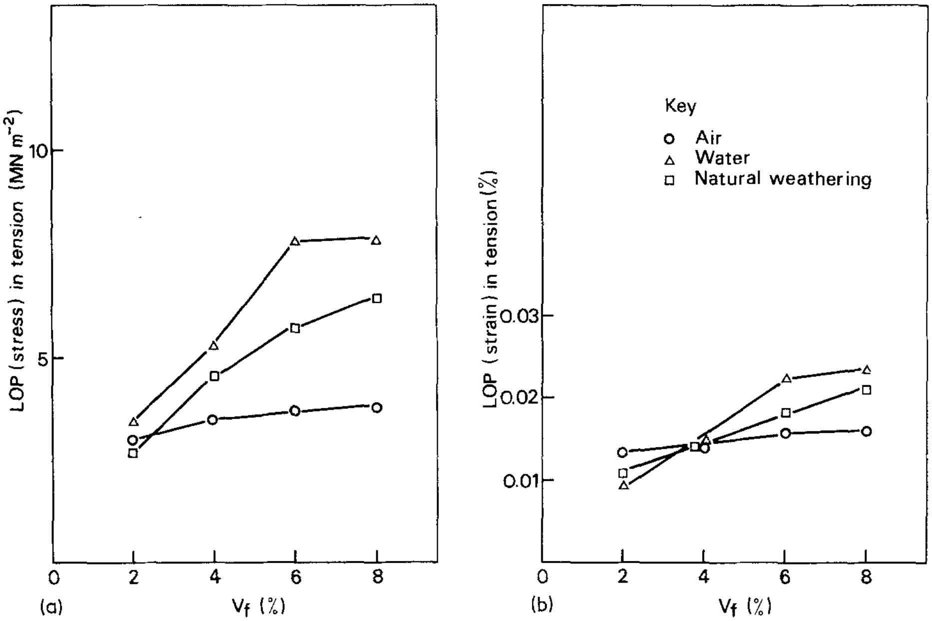

Figure 5 Relation between the limit of proportionality in tension and the fibre volume fraction at age 5 years. (a) Stress; (b) Strain.

In general the significance of the fibre length effect on tensile strength diminishes with increasing age, particularly in water storage or natural weathering conditions, whereas fibre volume fraction has a highly significant effect throughout. Fibre volume fraction is again a highly significant factor with respect to impact strength, while fibre length is of low significance except for material kept in dry air.

A more detailed three-way analysis of variance was possible on the bending strength data. In this case the previously mentioned "top and bottom" effect could also be investigated together with the main interactions between this and the other two factors.

The results confirm the importance of fibre volume fraction on the strength of grc at all ages and storage conditions (Figs. 1 to 3) but also show that fibre length has a significant effect on specimens up to 5 years old. Graphical analysis, how-

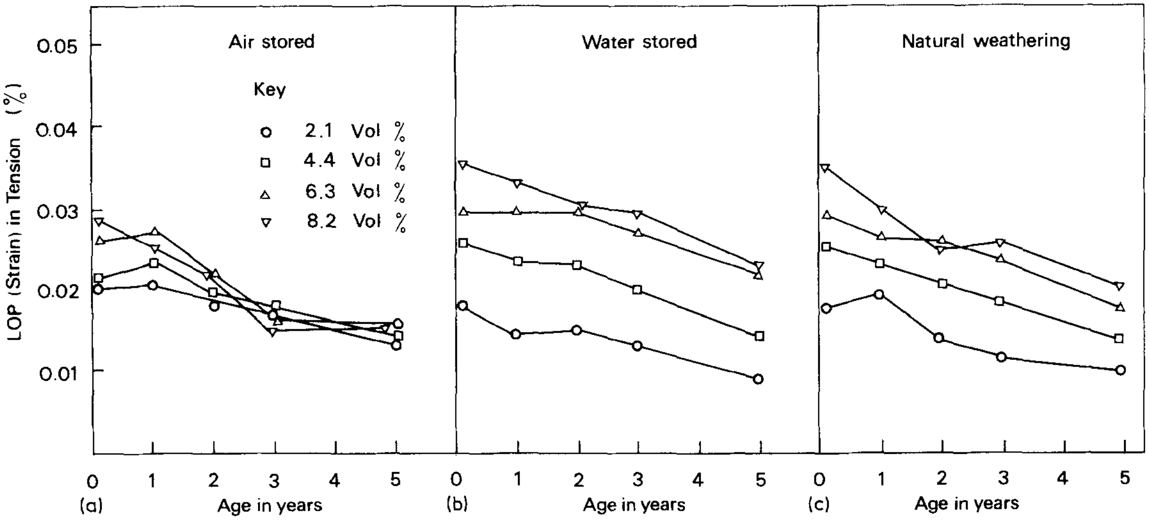

Figure 6 Limit of proportionality (strain) in tension at various ages for (a) air stored, (b) water stored and (c) naturally weathered grc.

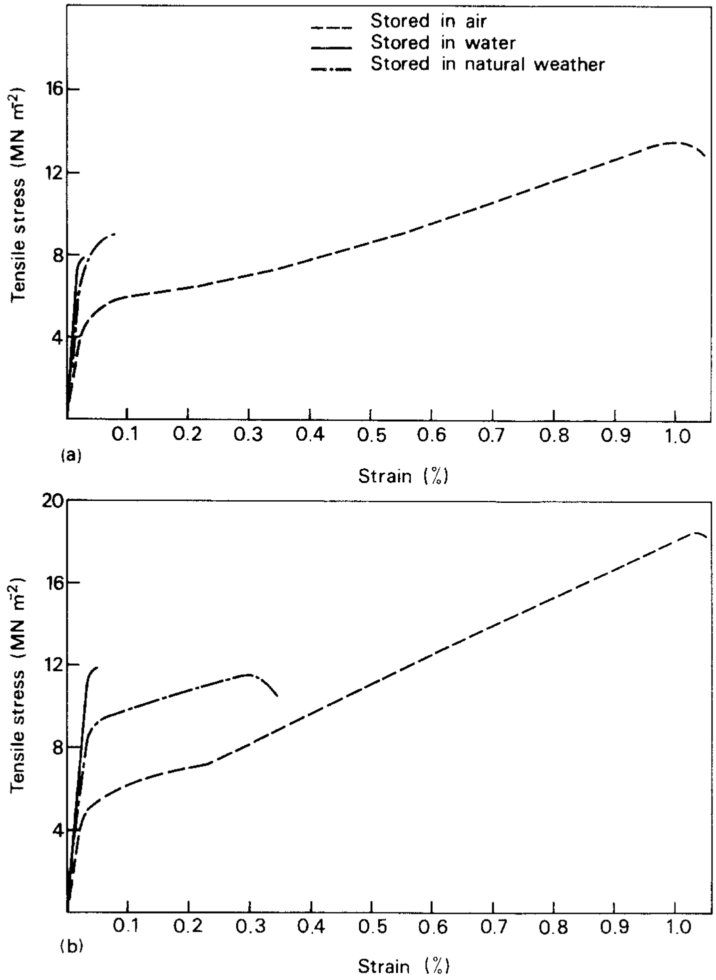

Figure 7 Tensile stress/strain curves of grc composites at age 5 years (a) 4.4 vol.% fibres, (b) 8.2 vol.% fibres. Fibre length 40 mm.

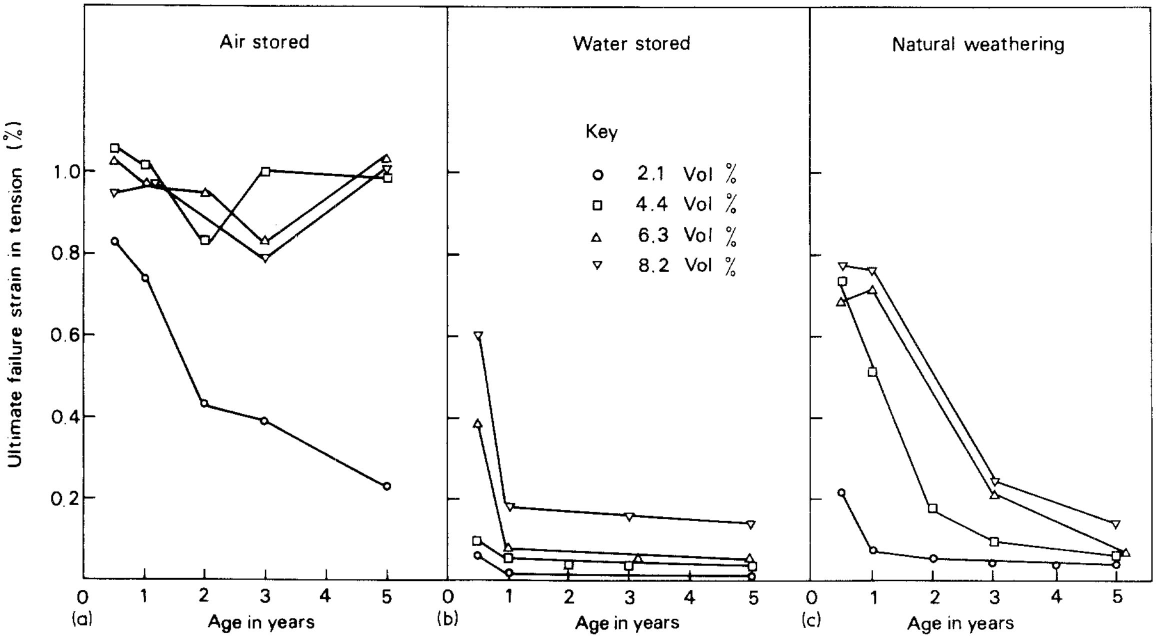

Figure 8 Ultimate failure strain in tension of grc composites at various ages. Fibre length 30 mm.

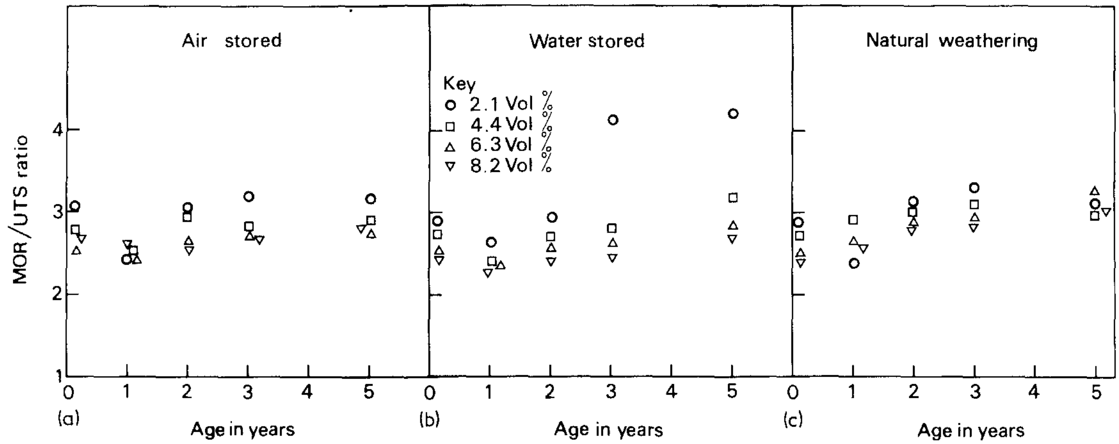

Figure 9 The variation of MOR/UTS ratios of grc with time.

ever, shows that the magnitude of this effect is small under conditions of water storage and natural weathering.

The "top and bottom" effect is generally of low significance overall but there is a strong interaction with fibre volume fraction. Graphical analysis shows that the orientation giving maximum flexural strength usually reverses as fibre volume fraction is increased (Fig. 11a). A similar but less pronounced effect is observed with respect to fibre length in some instances. (These effects may be related to the manufacturing process.)

A highly significant "top and bottom effect" is indicated for specimens subjected to natural weathering for 5 years and may be due to preferential weathering of the exposed surface. This effect is not evident at exposure periods of 1 year or less.

Fig. 11 is a graphical representation of the effects of "top and bottom effect", fibre length and fibre volume fraction on the flexural strength of grc under two widely different storage conditions (28 days in dry air at 20° C, and 5 years' natural weathering). In Fig. 11a the value of the flexural strength (MOR) is the average for all fibre lengths while in Fig. 11b the value is the average for all fibre volume fractions at the indicated fibre length. It can be seen that fibre volume

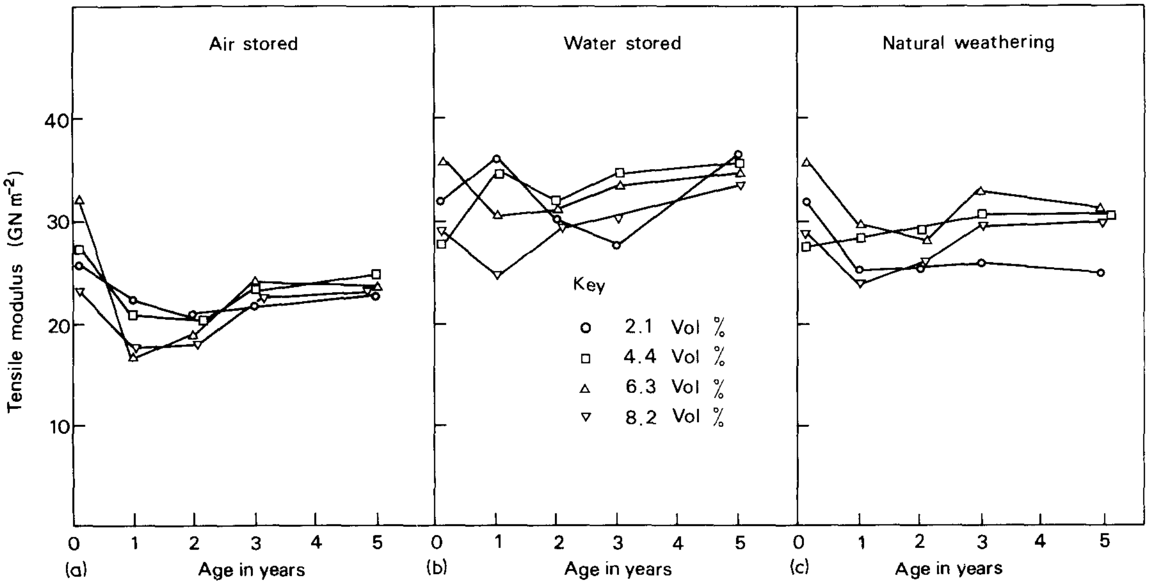

Figure 10 Tensile modulus of grc as a function of age and storage condition. (Average for all fibre lengths).

TABLE III Strength properties of grc stored at 90% r.h. and 20° C, or 40° C in dry air for 3 years

Fibre volume fraction (%)	Fibre length (mm)	MOR ($MN m^{-2}$)				Impact strength ($KJ m^{-2}$)			
		40° C air	20° C air at 40% r.h.	20° C air at 90% r.h.	20° C water	40° C air	20° C air at 40% r.h.	20° C air at 90% r.h.	20° C water
2.1	10	14.2	15.9	13.9	14.7	6.3	8.3	2.8	2.4
	20	12.6	19.4	12.0	14.4	6.6	9.8	3.7	3.5
	30	16.5	19.6	12.6	17.3	7.8	9.3	2.7	4.1
	40	17.2	21.5	12.9	15.1	9.5	10.3	3.1	3.0
4.4	10	21.7	26.6	19.9	20.5	12.4	14.2	6.0	5.0
	20	27.9	32.6	24.1	20.4	18.5	20.6	5.3	6.1
	30	29.6	38.2	23.0	23.7	21.3	23.6	7.2	6.6
	40	24.6	34.8	19.7	22.1	21.2	23.5	7.6	6.4
6.3	10	26.8	36.9	30.7	27.5	18.8	20.0	7.0	7.4
	20	27.2	43.1	29.4	31.0	25.9	32.1	13.6	9.4
	30	33.6	45.4	25.2	27.3	23.9	26.0	10.1	9.4
	40	33.3	51.7	27.0	33.6	31.2	36.0	10.3	13.3
8.2	10	31.2	39.0	25.4	32.0	32.2	34.2	14.1	14.3
	20	34.4	44.1	28.4	25.4	39.0	32.6	24.4	19.3
	30	43.3	51.1	33.2	39.2	32.5	38.5	17.5	17.8
	40	35.9	47.5	29.5	27.4	32.9	43.7	16.2	22.2

fraction has a strong influence on the bending strength of both new and weathered material but the effect of fibre length is much reduced after 5 years' natural weathering.

As far as the effects of hot and/or humid environments are concerned, the results given in Table III clearly indicate that very high humidity at 20° C is more deleterious to grc strength than relatively dry atmosphere at the elevated temperature (40° C). The corresponding results of accelerated ageing tests at 60° C under water show that in this environment grc strengths decreased in a continuous way with time for all fibre contents and reached matrix strength levels in 2 months. The fibre proportions in grc determined the time period over which composite strengths reduced to that of the cement paste.

5.2. Stress–strain

5.2.1. Matrix cracking

Like other brittle-matrix fibre composites grc is subject to "multiple cracking" [8] of the cement phase once the failure strain of this phase is exceeded. The limit of proportionality (LOP) values in bending and tension which mark the onset of matrix cracking, therefore, assume great importance in grc design. In the present work the LOPs have been taken as the points where the load–deflection curves in bending or the stress–strain curves in tension deviated from linearity. It would appear from the data in Table IV that for aged composites, the effect of fibre length on the LOP values is not very significant. These have, therefore, been averaged over all fibre lengths.

The data presented in Figs. 4 and 5a clearly

TABLE IV Matrix cracking stress (in bending and tension) of grc at 5 years having different fibre lengths and contents

Fibre length (mm)	LOP in bending ($MN m^{-2}$)						LOP in tension ($MN m^{-2}$)					
	4.4% (V_f)*			6.3% (V_f)			4.4% (V_f)			6.3% (V_f)		
	Air	Water	Weather	Air	Water	Weather	Air	Water	Weather	Air	Water	Weather
10	8.4	18.8	15.7	9.1	21.7	19.6	4.1	4.5	4.0	3.4	5.9	4.8
20	7.8	18.4	16.2	8.3	20.5	16.0	3.4	5.0	4.7	4.3	8.7	7.3
30	9.1	18.3	15.3	8.7	27.9	15.7	3.5	5.7	4.8	3.7	7.9	5.5
40	8.2	18.9	14.5	9.0	23.2	19.8	3.0	5.9	4.5	3.4	8.6	5.3

* V_f = fibre volume fraction.

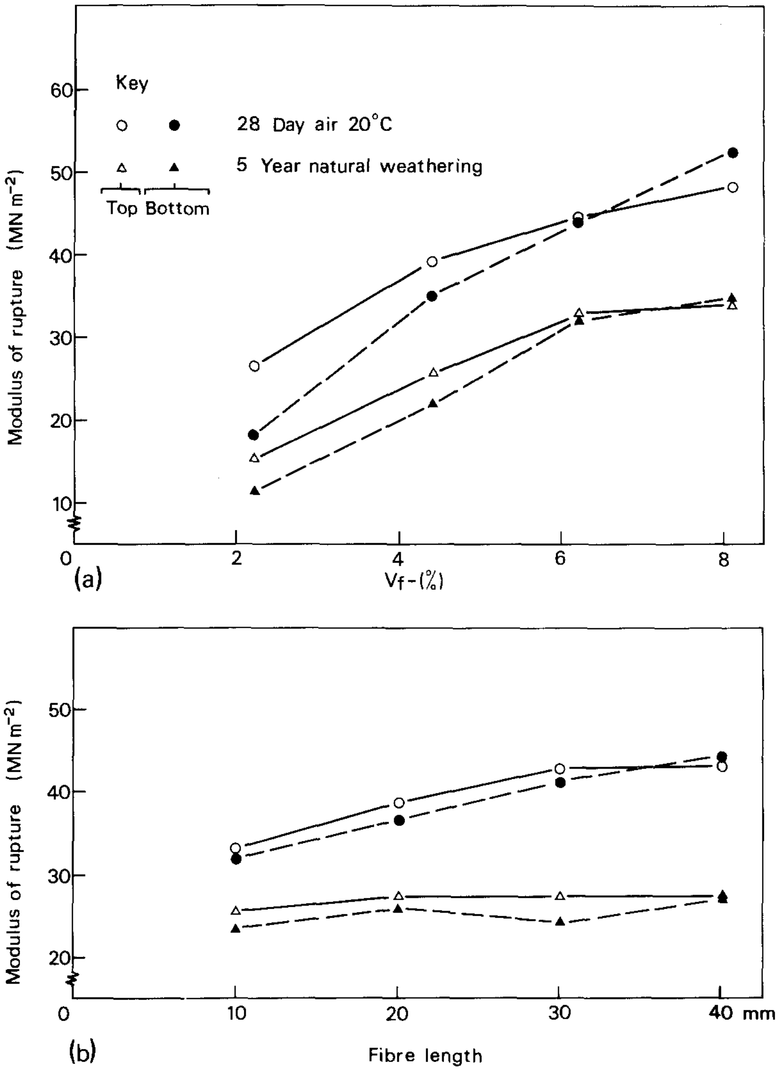

Figure 11 The influence of fibre length, fibre volume fraction and orientation at test (top and bottom effect) on the bending strength of grc at different ages. (a) Average for all fibre lengths, (b) Average for all fibre volume fractions.

demonstrated that in all environments, the LOP of grc in bending and in tension increases with an increase in fibre proportion. In so far as the LOP signifies the onset of multiple cracking in the matrix, present observations are compatible with theoretical predictions [8]. The LOP values are highest for water stored and lowest for air stored grc at all levels of fibre addition, reflecting the relation that exists between the degree of hydration of cement and the properties of the paste. Data not presented here tend to suggest that with time there is a slight decrease in the LOP values in bending when the grc composites are stored in dry air; the reasons for this are not clear.

For composites containing ~ 2 vol% fibre and kept continuously under water, the 5-year LOP values are nearly the same as ultimate strengths at all fibre lengths. At 28 days the ultimate strength values were higher and they showed an increase with increase in fibre length [5]. With the densification of the composite kept under water over a long period of time, debonding and pullout of fibres have virtually disappeared and the composite has failed by single fracture. It is also possible that for these composites (water stored for 5 years) ~ 2 vol% fibre level is close to or lower than the critical fibre volume fraction [8], in which case the multiple cracking of the matrix would not be expected. Without a knowledge of the actual strength of the fibre in aged composites this possibility cannot be verified.

The corresponding data on the matrix cracking strain in tension (Fig. 5b) show that these values increase with increase in fibre content (at all ages) and thus support the theoretical work of Aveston *et al.* [8]. A quantitative comparison of the observed effects with the theoretical predictions as made in the earlier study [5] was not attempted for aged composites because of the lack of information on some of the important parameters considered in the model.

When examining the effects of time and storage conditions on the matrix cracking strain (Fig. 6), it becomes apparent that there is a progressive reduction in strain values for all grc composites studied in the three environments used. The magnitude of reduction is appreciable from, say, 350 to 150 microstrain, and this observation seems to represent a real effect for which no adequate explanation can be offered at present.

5.2.2. Composite failure

When the tensile stress–strain curves of grc kept in different environments for 5 years (Fig. 7) are compared with those obtained after 28 days, it becomes obvious that in wet environments the material undergoes significant changes. Whereas the failure strain for the composite containing the smallest proportion of fibre (~ 2 vol%) is of the order of 4000 microstrain after 28 days in water, it is no more than 200 microstrains after 5 years under the same conditions even for the composite containing ~ 8 vol% of fibre. In other words grc eventually becomes an essentially brittle material if used in wet environments. The composites with the higher proportions of fibre studied in the present work still retain some pseudo-ductibility after 5 years' natural weathering at Garston. If stored in relatively dry air this particular property of grc, characteristic of the material of young ages in all environments, remains nearly unaffected with time. This is more clearly illustrated in Fig. 8. It can also be seen that when kept continuously immersed in water, the failure strain of grc decreases very rapidly in the first year and then probably approaches the matrix value with time. In natural weathering the decrease with time is a much slower process, particularly at the higher fibre levels. The changes in the failure strain of grc with time thus show the same trends as the UTS.

5.3. MOR/UTS ratio

It has been mentioned in previous publications and also here that on prolonged storage in wet environments grc becomes essentially a brittle material. As is well known, the determination of the tensile strength poses difficult problems for the experimentalist and aged grc is no exception [9]. Previous experience with grc kept in both dry and wet environments indicated that the UTS changed with ageing in a way that roughly paralleled the MOR and that the ratio of MOR to UTS was about 2.5 : 1 for all ages beyond the very early stage of cure [3]. Some idea of the tensile strength of grc can, therefore, be obtained from the bending results.

The range of MOR/UTS ratios derived from the present work are summarized in Fig. 9 for the three storage conditions. It is seen that in many instances, particularly with weathered samples the MOR/UTS ratios are higher than 2.5 and have sometimes exceeded 3. It is also noticeable that there is a trend for these values to increase with the age of the sample and also that composites with low glass contents have usually given high MOR/UTS ratios.

The theoretical maximum value for the MOR/UTS ratio of non-linear materials such as fibre cement compositions has been shown by Aveston *et al.* to be 3 [10]. Some of the observed values in the present study are therefore open to question and in view of the difficulties experienced with some of the specimens, arising from distortion and non-uniformity in the samples (similar to those described by Green *et al.* [9]), it would not be surprising if the measured UTS values were underestimates. On the other hand it must be recognised that the theoretical analysis referred to above does not take into account any "size effect" or the very different modes of failure in bending and tension for the brittle-matrix fibre composite material. A further complication as far as the present results are concerned is the changing nature of grc with time. What the theoretical MOR/UTS ratio should be for such a material in different periods of its life requires further clarification.

5.4. Young's modulus

The variations in the Young's modulus values of grc (containing different amounts of fibre) with time and storage conditions are shown in Fig. 10. At each level of fibre addition, the values have been averaged over the four fibre lengths studied. It is seen that the water-stored samples have given the highest long-term values and those kept in relatively dry air the least. Weathered samples have given intermediate values. With small percentages of fibre reinforcements used in this study, the Young's modulus of the composite is largely dependent on the matrix and hence on the degree of hydration of cement.

6. Conclusions

A substantial amount of experimental data on the mechanical properties of grc, containing different amounts of Cem–FIL AR glass fibres of different lengths and kept in three different environments for up to 5 years, are presented in this paper. Where comparable results on the durability of grc are available (see [3]), present results indicate that in well-made grc the age–strength relationship is reproducible. The present work also confirms the earlier findings that when grc is used in a relatively dry environment, its bending, tensile and impact strengths are not greatly affected by age but the LOP in bending is reduced. In wet environments the LOP values show an increase with time but the ultimate strength properties deteriorate.

In considering the durability of grc the proportion of fibre per unit volume of hydrated cement is an important parameter. The cement phase in grc hydrates to different extents in different environments: for instance a significant amount of unhydrated cement is still present in grc exposed to weather at BRE for 10 years. With progressive hydration of cement in grc those properties of the composite (e.g. density, Young's modulus, LOP, etc.) which essentially depend on the matrix show an increase. On the other hand, fibre strength decreases, more significantly if the temperature is raised, and a considerable densification of the interface takes place [11]. Regarding the latter phenomenon, nucleation and crystal growth of the products of cement hydration, notably $Ca(OH)_2$, at the interface are important factors. The loss of pseudo-ductility of grc in wet environments, reflected in poor impact strength, is directly related to the densification and corrosiveness of the cement matrix. Obviously, in composites containing larger proportions of fibres, the cumulative effects of cement hydration will take longer to show. If the hydration of cement is arrested, as is the case in relatively dry atmosphere, or if it proceeds slowly, as may be the case with natural weathering, the reduction in grc strength properties is expected to be far less than in a continuously wet environment. The results presented in this paper by and large substantiate this view.

It should be noted that predictions have been made on the 20-year properties of standard grc (i.e. containing 4 vol% of 34 to 38 mm long fibre) based on extrapolation of experimental data of up to 5 years [3, 4] and some attempts have been made to estimate even longer terms properties [12]. In these predictions a considerable volume of results collected over many years has been used. It is felt that the data accumulated in the present study are not sufficiently extensive at each fibre level to justify a rigorous statistical analysis leading to very long-term predictions. This remains as an objective for the future.

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