5 Durability of GRC with Modified Matrices and Glass Mesh

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Abstract: It is well known that there is a loss of strength and ductility of GRC with time. In the early 1980s Litherland et al investigated correlations between accelerated ageing regimes and natural weathering using materials at the time and developed an empirical durability model. In modern GRC, matrices are often modified with pozzolanic materials, polymers etc. and glass reinforcement is also available in mesh and mat form. For some of these new materials, very limited test data are available regarding ageing performance. It is not clear whether the acceleration factors originally suggested for older GRC formulations are valid for these new materials. Results from hot water ageing on GRC samples made with VCAS pozzolan and polymer modified matrices and samples made with glass mesh reinforcement is presented and compared with current ageing models. A durability model based on the study of FRP reinforcement in concrete is adapted to GRC. By applying various ageing condition terms, data from accelerated ageing tests can be correlated to the natural weathering condition and consequently to predict the service life.

Keyword: GRC, VCAS pozzolan, acrylic polymer, glassfibre mesh, LOP, MOR, STF, durability model, acceleration, retention

1. Introduction:

Early formulations of GRC made from ordinary Portland cement (OPC) and first generation alkali resistant (AR) glassfibres are known to lose some of their strength over time particularly when they are exposed in a hot and damp or wet environment (Majumdar and Laws, 1991). MOR and strain to failure decline to a stable level with the MOR converging very close to the long term LOP, which itself tends to rise slightly due to continuing cement hydration (Figure 1). For safety, strength loss needs to be taken into account during design. Various approaches proposed to improve the ageing performance of GRC have been reviewed by many authors (Bentur and Mindess 1990; Bijen 1993; Hayashi et al. 1993; Purnell et al. 1999; Cheng et al. 2003; Cui et al. 2008). These generally fall into two categories: 1) changing the chemical composition of glass fibres or their surface treatment 2) modifying the matrix.

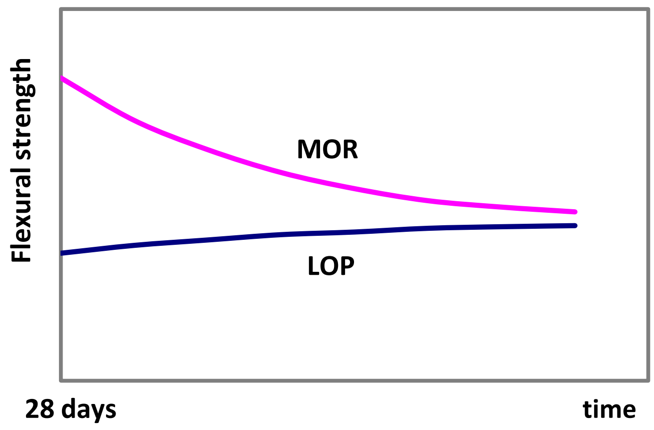


Figure 1 Long term flexural strength declining

Materials being reported to improve GRC durability through modifying the matrix include calcium sulphoaluminate (Cui et al. 2008), metakaolin (Thiery et al. 1991; Zhu and Bartos 1997), microsilica (Marikunte et al. 1997) or acrylic polymer (Ball and Wackers 1995). The latest material developments include VCAS, a ground E glass fibre pozzolan and AR glass fibre mesh, a structured form of glass reinforcement.

The introduction of new materials requires the development of new knowledge on long term strength retention under working conditions. This should be ideally obtained from exposure of test samples at the expected working conditions over a lifetime, which often extends over many tens of years. It is therefore necessary to develop some means of accelerating normal ageing and, hence, the ability to predict long term strength.

An empirically derived durability model was developed by Litherland et al. (1981) from studies on GRC in production at the time. This model gives a correlation between hot water accelerated ageing and natural weathering. This model was presented in terms of acceleration factors, e.g. 50 °C for 84 days or 60 °C for 40 days are considered equivalent to 30 years of natural exposure in a central European climate (Gartshore et al. 1991; Gartshore et al. 1998; Glinicki 1998).

The model was developed before new materials were available. It is not clear whether the acceleration factors originally suggested for older GRC formulations are valid for these newer materials. Hence, there is a need for verification and even the development of new approach. For the new GRC raw materials, this paper focuses on VCAS pozzolan, acrylic polymer and glass fibre mesh.

2. Materials and specimen preparation

2.1 VCAS pozzolan

Three 1.2×1.2m GRC boards were made by the hand-spray method. The mix design for the three boards were,

Mix O: standard GRC mix (sand:cement:water=1:1:0.32, 1% Superplasticiser by weight of cement, 5% fibre);
Mix V: same as Mix O, but with 25% replacement of OPC with VCAS pozzolan;
Mix P: same as mix V, but with additional 10% acrylic polymer emulsion on the combined weight of Cement and VCAS pozzolan.

After 28 days each board was cut into 64 standard (EN1170-5, 1998) test coupons (Figure 2), amongst which 8 were used as control coupons and 56 were placed in water baths at 60 °C (Figure 3). Bending tests were conducted according to EN1170-5 (1998) at various ageing times.

Figure 2 Test coupons

Figure 3 60 °C hot water bath

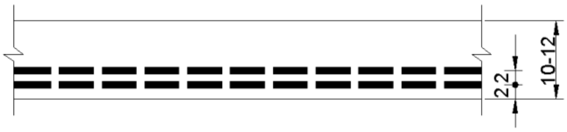
2.2 Glass fibre mesh

Premix GRC with 2.5% chopped strands at w/c ratio 0.32 was used to cast 1m×1m test board (Figure 4). Different types of glass fibre mesh were placed in the board either in one layer or two layers as shown in Table 1. A GRC panel without net reinforcement was also cast as a control specimen.

Figure 4 Mould and test board casting

Table 1 Glass fibre mesh reinforcement and its position in the board

Board	Mesh size (mm)	Density (g/m2)	Layers
A	Control sample		
B	10×10	150	Double
C	5×5	160	double
D	5×5	160	single
E	6×6	270	single
F	4×4	180	single
G	10×10	150	single



Position of glass fibre mesh in the board

After 28 days, each board was cut into 36 test coupons, amongst which 4 were used as control samples and 32 were immersed in a 60 °C hot water bath. Standard bending tests (EN1170-5:1998) were conducted at various ageing times.

3. Results

3.1 VCAS pozzolan and acrylic polymer

Table 2 shows the ageing test results for the samples mentioned above. The time taken for a given properties (MOR and strain to failure (STF)) to be reduced to half its original, unaged value ($t_{50\%}$) is compared in Figure 5 . The $t_{50\%}$ of MOR and STF for matrix V and matrix P GRC were about 4 times and 2 to 3 times longer than for matrix O, respectively. This indicates that the VCAS pozzolan can improve the durability and ductility of GRC effectively. The further addition of acrylic polymer showed little effect. The results from these tests will be discussed further in the following sections.

Table 2 Ageing test results

Ageing time(day)		0	3	10	20	30	40	50	70	80	90
Mix O	MOR(MPa)	25.39	18.06	15.04	12.33	12.32	10.75	10.61	11.01	10.55	10.93
	STF (%)	1.07	0.72	0.53	0.33	0.29	0.163	0.1234	0.106	0.089	0.09
Mix V	MOR(MPa)	19.92	16.89	15.99	14.75	14.29	13.76	11.91	10.28	9.9	9.93
	STF (%)	1.34	0.97	0.88	0.62	0.48	0.395	0.257	0.15	0.09	0.12
Mix P	MOR(MPa)	23.42	19.96	18.46	15.94	15.57	15.09	13.22	12.71	11.72	11.58
	STF (%)	1.02	0.95	0.78	0.85	0.42	0.31	0.20	0.13	0.10	0.12

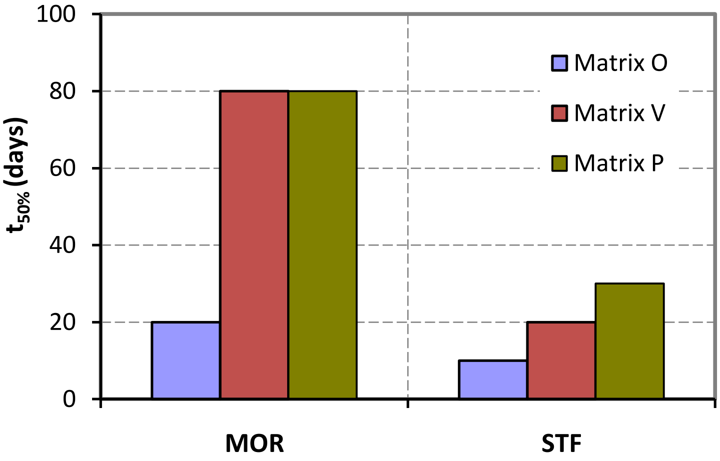


Figure 5 Comparison of $t_{50\%}$ values

3.2 Glass fibre mesh

Results of MOR and STF at different ageing time are shown in Table 3.

Table 3 Ageing test results

Ageing time (day)	Properties	Sample board						
		A	B	C	D	E	F	G
0	LOP (MPa)	7.45	8.46	8.26	8.70	8.41	9.92	8.82
	MOR (MPa)	8.89	22.95	19.88	14.09	21.83	21.14	14.38
	STF (%)	0.41	1.16	1.01	0.55	1.25	1.16	0.81
10	LOP (MPa)	7.02	7.69	8.43	8.41	7.60	8.92	8.22
	MOR (MPa)	8.38	20.84	19.09	12.21	19.30	17.54	12.29
	STF (%)	0.34	1.00	0.91	0.52	1.07	1.00	0.66
20	LOP (MPa)	6.84	7.70	7.81	7.70	6.84	7.34	6.93
	MOR (MPa)	7.66	18.08	16.04	10.26	16.35	14.30	9.95
	STF (%)	0.28	0.92	0.73	0.39	1.16	1.01	0.76
30	LOP (MPa)	7.05	7.08	7.71	7.85	7.65	8.33	7.62
	MOR (MPa)	7.35	15.27	13.78	10.16	15.20	12.98	10.39
	STF (%)	0.21	0.86	0.62	0.28	0.97	0.84	0.65
45	LOP (MPa)	6.74	6.99	8.36	8.68	7.90	8.73	7.78
	MOR (MPa)	6.77	13.44	13.72	10.02	15.79	12.60	10.24
	STF (%)	0.11	0.70	0.60	0.21	0.86	0.69	0.30
60	LOP (MPa)	6.88	7.24	7.84	7.78	7.77	8.62	7.09
	MOR (MPa)	6.71	11.17	12.55	9.35	11.50	11.00	10.17
	STF (%)	0.09	0.46	0.46	0.20	0.54	0.47	0.30
75	LOP (MPa)	7.14	7.46	7.67	8.66	7.65	8.87	8.52
	MOR (MPa)	6.57	11.68	11.82	9.34	11.13	11.31	9.90
	STF (%)	0.05	0.41	0.41	0.18	0.42	0.41	0.25

The MOR and STF, the retention of MOR and STF after the accelerated ageing period, as a percentage of the unaged value, are plotted in Figure 6 and Figure 7.

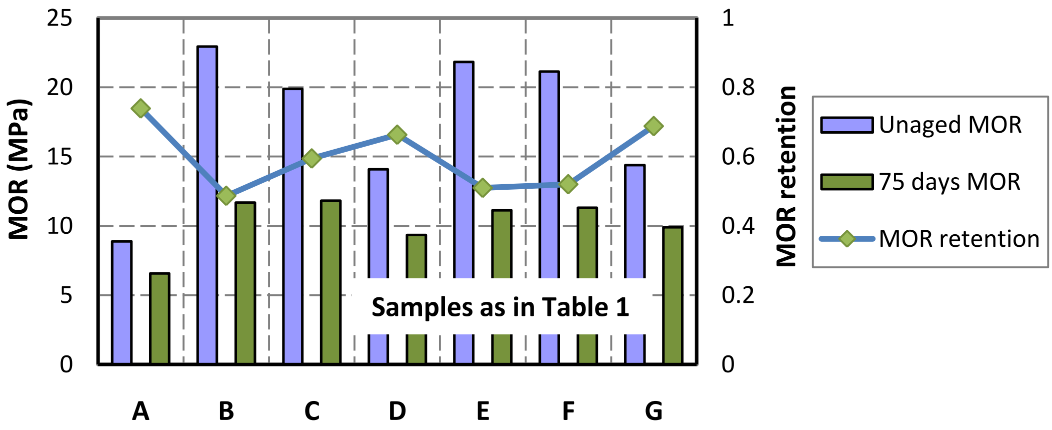


Figure 6 Residue MOR after 75 days accelerated ageing

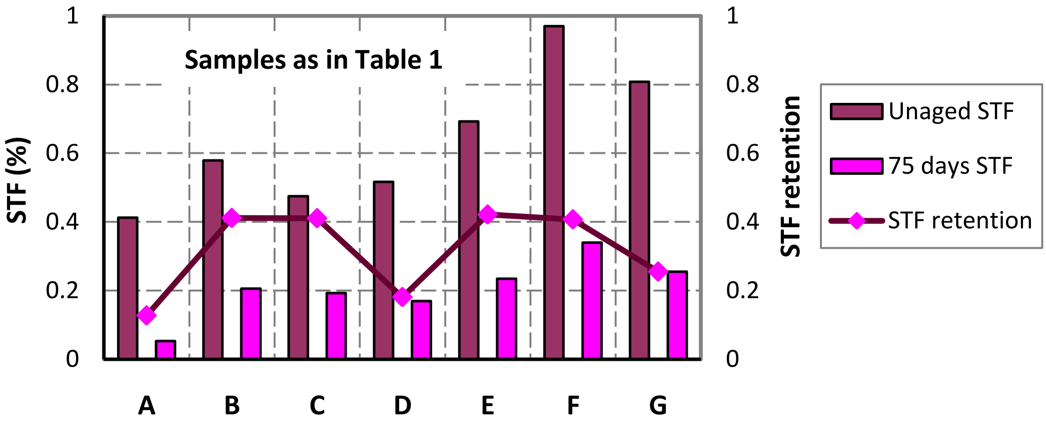


Figure 7 Residue STF after 75 days accelerated ageing

The initial strength and STF of GRC reinforced with glass mesh increases as compared with unreinforced GRC. Whilst the addition of mesh increased the long-term ductility of GRC substantially (with the STF retention between 20-40% after 75 days of ageing compared to 12% of unreinforced GRC), the strength retention is a bit lower than pure GRC (50-70% to 73%). Nevertheless, the residual MOR of mesh reinforced GRC is still higher than that of plain GRC (see Table 3).

In general, higher reinforcement ratios result in higher initial MOR. However, a double layer of reinforcement is not as efficient as a single layer in enhancing the initial ductility, possibly because the failure of the bottom layer takes place first. Although there is significant difference among the initial MOR and STF, the aged values all become comparable.

3.3 Normalised strength vs. logarithmic time

The basis of the Litherland et al. (1981) model is that up to the point where GRC degradation stabilises, a plot of composite strength vs. logarithmic time will produce a straight line. Figure 8 and Figure 9 plot normalised strength vs. log [aging time]. The 60 °C strength data used in the formulation of Litherland et al. model is also plotted for comparison. MOR data are normalised with respect to their initial, unaged values.

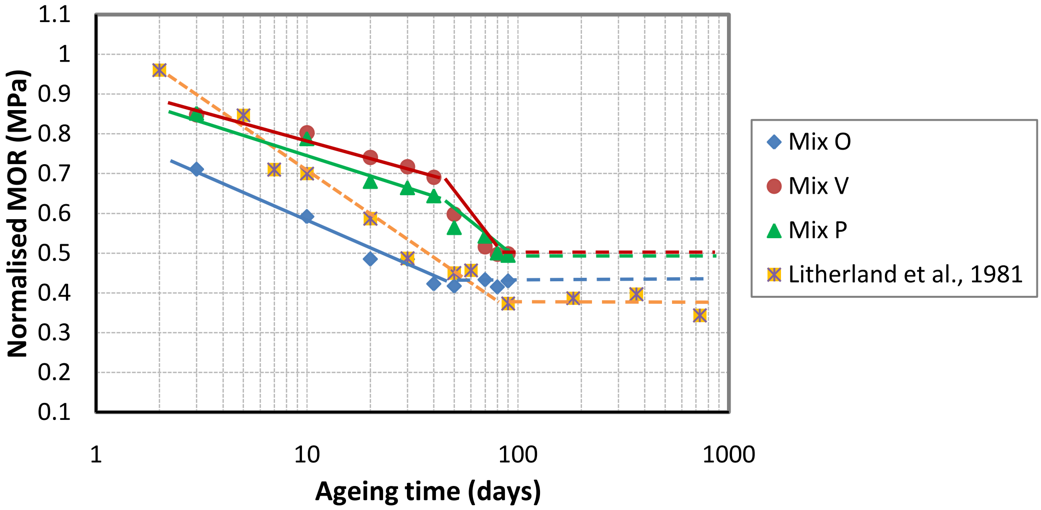
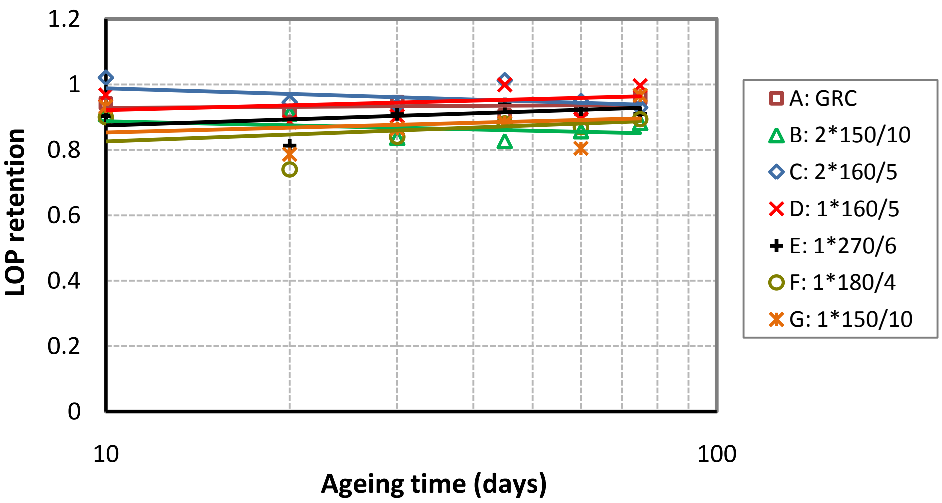


Figure 8 Modified matrix GRC ageing performance

Mix O GRC behaves in a comparable way to that used to formulate the model. Mix V and mix P GRC exhibited a rather better behaviour, the rate of strength loss increasing with logarithmic time giving the appearance of a two-stage process. GRC strength is clearly not inversely proportional to logarithmic time for the modified matrix GRC. Hence, since the central assumption of the Litherland et al. model appears invalid for modified matrix GRC, caution is necessary when applying it to justify hot water accelerated ageing tests.

GRC degradation stabilisation occurred at 40 days for mix O GRC and around or just beyond 3 months for the modified matrix GRC. The addition of polymer did not show a positive effect in terms of retarding the ageing process. For mix O GRC, there is a linear initial fall in strength and then a sharp transition to the constant strength region for the remainder of the ageing period. This can be regarded as a ‘fully aged’ condition for GRC. In this case, this is around 40% (11.5MPa) of the unaged strength. This value is likely to be very close to the LOP for the particular mix.



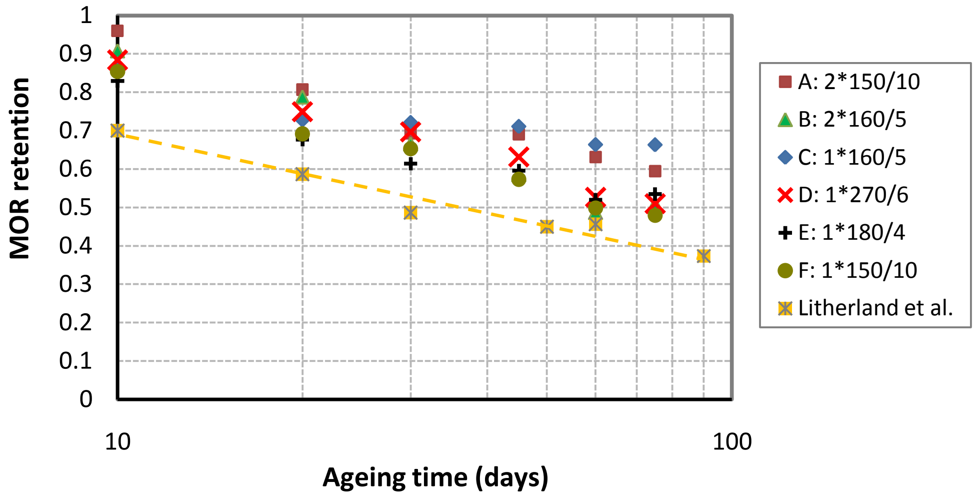


Figure 9 Fibre mesh reinforced GRC ageing performance

The ageing values of LOP remain more or less constant at around 80-100% of the initial value for both plain GRC and mesh reinforced GRC. This confirms that LOP is mainly related to the matrix and matrix made with OPC is stable when exposure to the wet environment. MOR reduces linearly with logarithmic time, so these samples deteriorate in a similar way as those used to formulate the Litherland et al. model. However, all the MOR retention data are above the Litherland et al. model data, which means the ageing process is slower. This may be due to the fact that glass fibre bundle is protected by the polymer coating used to manufacture the mesh.

It is anticipated that the long-term strength of any GRC sample will tend to be the LOP value, hence, the MOR retention should stabilise at the LOP/MOR ratio. This is as predicted by Figure 1 and as shown in Figure 8. Hence, a better way to examine GRC degradation is by looking at the (MOR-LOP) retention. The normalised value of difference of MOR and LOP vs. log [aging time] is plotted in Figure 10.

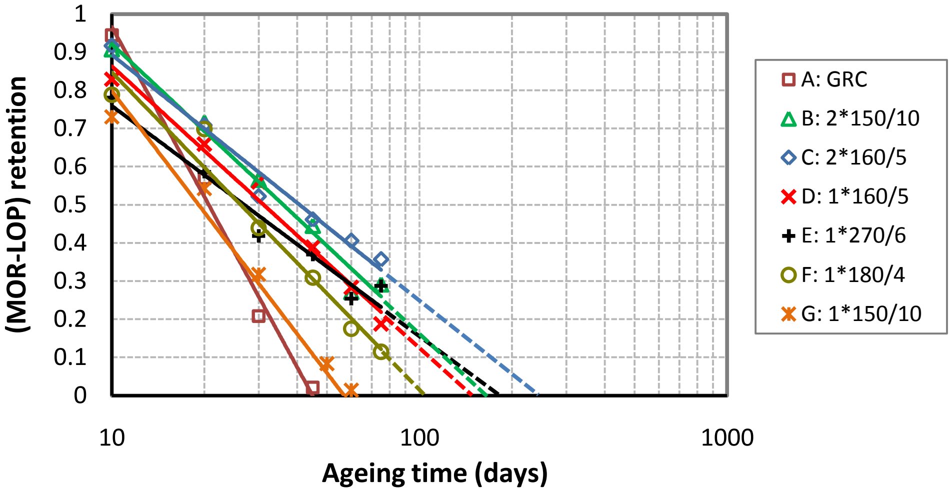


Figure 10 Relation of (MOR-LOP) vs. ageing time

It clearly shows that the value of (MOR-LOP) is still inversely proportional to logarithmic time. The intersection on the x-axis indicates the time it takes for GRC to be 'fully aged'. The 'fully aged' time and reinforcement rate of each sample is shown in Table 4. It can be seen that a higher reinforcement ratio generally leads to a prolonged 'fully aged' time.

Table 4 Reinforcement rate and 'fully aged' time

Sample	A	B	C	D	E	F	G
Reinforcement ratio (g/m^2)	0	300	320	160	170	180	150
'Fully aged' time (day)	42	146	220	128	163	101	56

It is evident that by applying old models to new formulations of GRC, can lead to over- (or under) estimation in strength retention with potentially serious consequences. Further work needs to be done to propose a durability model.

4 GRC fence panel after five years' natural weathering

A premix GRC fence panel (Figure 11) was cast for a final year project by an undergraduate student of the University of Sheffield and was stored in the mist room (20 °C and 100% RH) for standard curing. The basic mix design was cement:sand:water=1:1:0.35 with 2.5% glass fibre. After five years, twelve test coupons (Figure 12) were cut from the panel and flexural strength was tested.

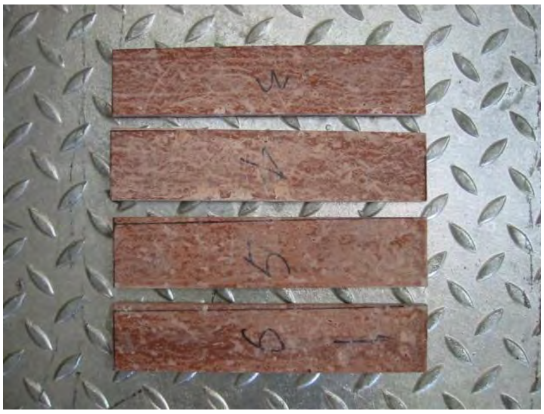


Figure 11 GRC fence panel

Figure 12 Bending test coupons

The average MOR of 12 test coupons was examined to be 7.73 MPa, the original MOR obtained from testing GRC coupon of the same mix design was 8.95 MPa (Kiratzis 1999). The normalised strength vs. log [aging time] of this result together with the results of 60 °C hot water ageing on premix GRC with a similar mix design (Table 3) is shown in Figure 13.

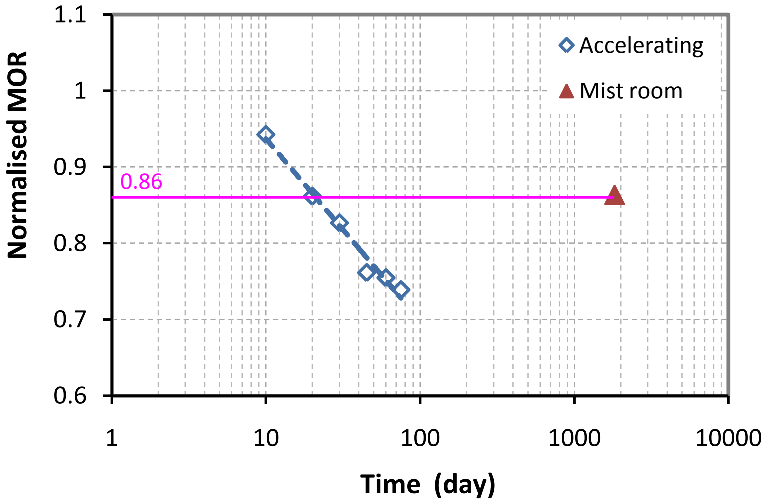


Figure 13 OPC GRC ageing performance

To correlate the above data, and more importantly, to predict GRC durability in the natural environment, a durability model needs to be adopted.

5. Durability model

As GRC material degrades through its entire service life, it is necessary for design engineers to choose the appropriate long-term strength as the design value. Due to the test time limits, such strength can only be predicted by using durability models.

It is proposed that GRC is designed for durability on the basis of a simple design strength equation, in which the characteristic bending strength is multiplied by a factor which is linked to various environmental parameters and divided by a material safety factor as shown in Equation 1.

$$f_{GRC,d} = \kappa_{env,t} MOR,_0 /(\gamma_{GRC}) \qquad (1)$$

where $f_{GRC,d}$ is the strength design value, $MOR_{,0}$ is the original bending strength, $\kappa_{env,t}$ (=1/ $\eta_{env,t}$) is the environmental strength retention factor and is the ratio between long-term and original strength, $\eta_{env,t}$ is the strength reduction factor, γ_{GRC} is the material safety factor.

A similar approach has also been adopted by the fib in Bulletin 40 (fib 2007) when dealing with FRP as reinforcement in concrete.

5.1 Environmental strength retention factor ($\kappa_{env,t}$)

This factor can be determined accurately if the 1000h strength $f_{fk,1000h}$ and the standard reduction of strength per logarithmic decade due to environmental influence R_{10} is known (Figure 14). It is expected that there is a shift of about three logarithmic decades from 1000h to 880,000h (100 years) or 2.7 logarithmic decades for 50 years life. The following power equation can be used to calculate $\kappa_{env,t}$ (adapted from German Standard (DIN 1990)).

$$\kappa_{env,t} = (1 - R_{10})^n (f_{fk,1000h} / f_{fk,0}) \qquad (2)$$

where $f_{fk,0}$ is the original strength, and for normal environmental and service conditions n equals 3.

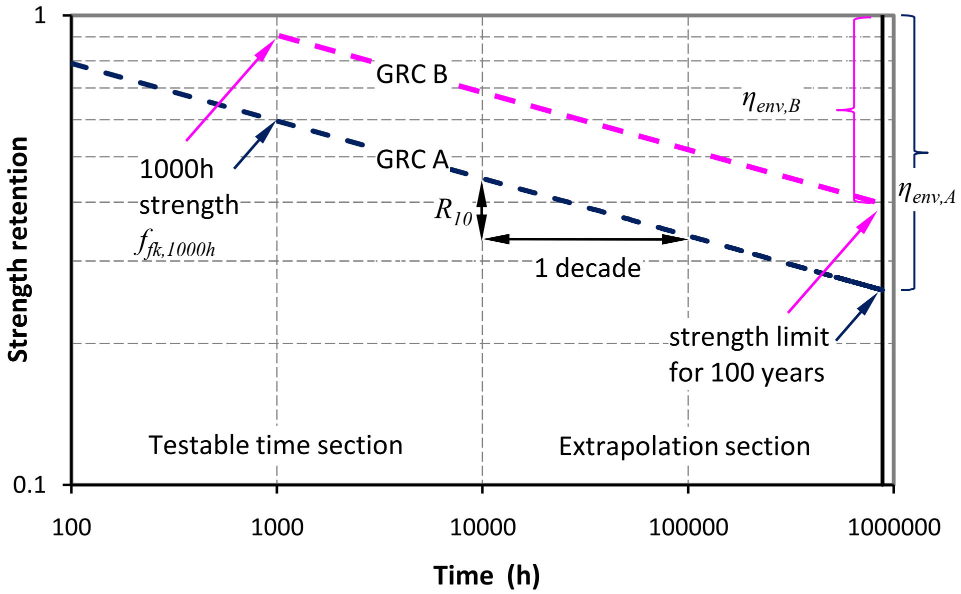


Figure 14 Environmental strength retention factor and 1000 h strength for two different GRC materials with different durability (adopted from fib bulletin 40)

If no long term retention factors are known, an estimation using the above approach can be used. Therefore the 1000h value is determined from short term data of MOR and literature data on strength retention. The following equation was adapted from Weber (2006),

$$\kappa_{env,t} = (1 - R_{10})^{n+2} \tag{3}$$

where n is the sum of the different influence terms

$$n = n_T + n_{mo} + n_{SL} \tag{4}$$

where n_T is the term for temperature (Table 6), n_{mo} is the term for moisture condition (Table 7) and n_{SL} is the term for desired service life (n_{SL} = log [time]+1, time in year) (DIN 1990; Weber 2006), typical n_{SL} values are shown in Table 5.

Table 5 Term for desired service life

Service life (year)	1	10	50	100
n_{SL}	1	2	2.7	3

5.2 Terms for temperature (n_T)

GRC material deterioration can be assumed to be substantially a chemical process even when the cause of deterioration is the expansion of the hydration products penetrating into the fibre bundle and the attack at the individual filaments due to alkalinity or stress due to lateral pressure. Chemical reactions in general double their rate every 10 °C and that is why a linear relationship can be found between the strength retention and logarithmic time. In stress corrosion tests (fib 2007) the reduction factor of 10 °C was observed to be higher, reaching value between 2.25 and 2.85 (Weber 2005). The fib Bulletin 40 (fib 2007) proposes a logarithmic shift of 0.5/10°C which means that the acceleration factor of $\sqrt{10}$ is obtained for each logarithmic decade as shown in Table 6 and Figure 14 .

Table 6 Term for mean annual temperature (MAT)

MAT (°C)	<5	5-15	15-25	25-35
n_T	-0.5	0	0.5	1

5.3 Terms for moisture condition (n_{mo})

It is accepted that the rate of deterioration of GRC largely depends on the environmental humidity (Proctor et al. 1982). This was demonstrated earlier in Chapter 3 when exposing the glass fibres in simulated cement pore solution. Byars et al. (2001) proposed three humidity conditions:

1) Dry: Indoor condition, protected from rain with an average relative humidity of approximately 50%.

2) Moist: Outdoor conditions, subjected to rain but not constantly in contact with water with an average relative humidity of approximately 80%.

3) Saturated: Constantly in contact with water with average relative humidity close to 100%.

The accelerating effect of these conditions in logarithmic term is given in Table 7 and also shown in Figure 15.

Table 7 Correction term for moisture condition of GRC

Condition (RH)	Dry (50%)	Moist (80%)	Saturated (100%)
n_{mo}	-1	0	1

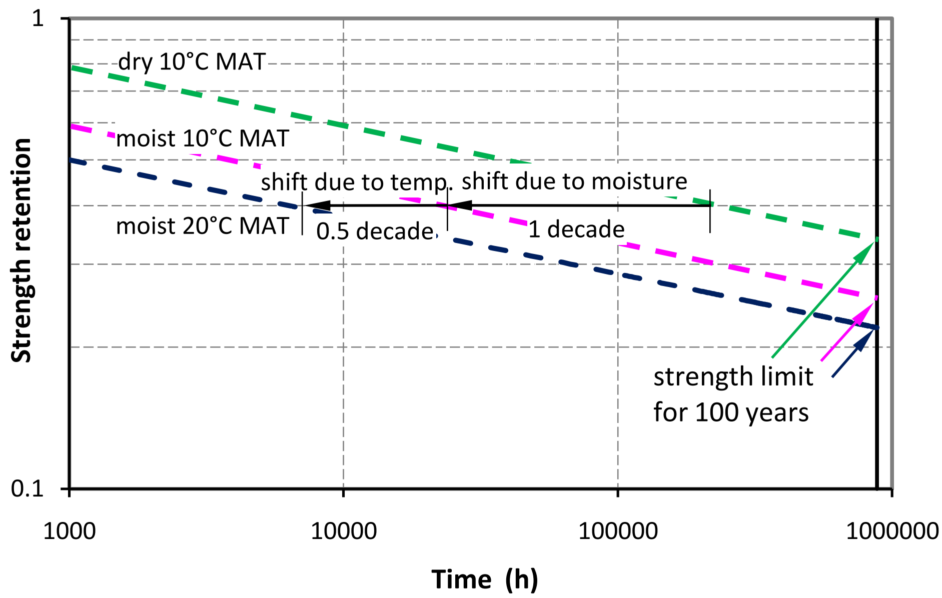


Figure 15 Effect of the parameter of temperature and humidity on GRC flexural strength retention curves (adopted from Weber (2006))

5.4 GRC long-term strength prediction

If we accept that the strength degradation in GRC is mainly due to the degradation of the glass fibre, then the strength degradation should stabilise when it reaches the level of LOP. Hence, the degradation behaviour in double logarithmic scale should be bi-linear with the second branch being horizontal. The first branch is the one that provides the value of R_{10}. R_{10} can be obtained by conducting the following procedure: firstly the MOR retention vs. time (in hour) is plotted on a double logarithmic scale, then a power trend line, which displays as a straight line on the double logarithmic scale, is drawn against this plot. The absolute value of the exponent of the trend line is taken as R_{10}. R_{10} values are calculated for the GRC ageing samples as shown in Table 1. The results for sample A and sample C are shown in Figure 16. A summary of the ratio of LOP and MOR, R_{10}, $\kappa_{\mathrm{env},50}$, $\kappa_{\mathrm{env},100}$, and t_{LOP} are shown in Table 8. $\kappa_{env,50}$ and $\kappa_{env,100}$ are the strength retention after 50 and 100 years, respectively. t_{LOP} is the time in years by which the glass fibres deteriorate completely and GRC strength drops to the value of LOP. This value is marked as >100 when it exceed 100 years.

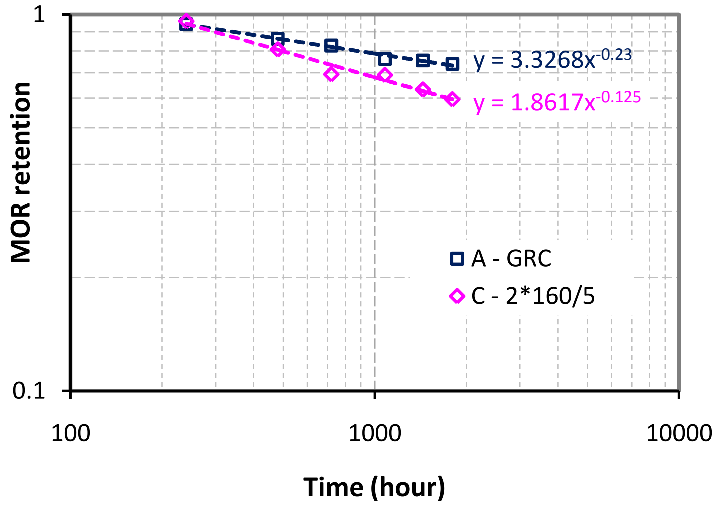


Figure 16 MOR retention vs. time and R_{10}

Table 8 Durability prediction

Sample	MOR/LOP	R_{10}	$\kappa_{env,50}$	$\kappa_{env,100}$	t_{LOP} (year)
A	1.19	0.125	0.85	0.82	63
B	2.41	0.322	0.63	0.56	>100
C	2.71	0.230	0.73	0.68	28
D	2.59	0.123	0.85	0.82	>100
E	2.13	0.277	0.68	0.61	>100
F	1.62	0.224	0.74	0.68	>100
G	1.63	0.288	0.67	0.60	87

The conventional GRC sample A has a lower R_{10} value, but that is because the MOR/LOP ratio is relatively low. From the other samples, in general, higher reinforcement ratios result in higher MOR/LOP ratios and lower R_{10} values, which lead to a much better durability.

In order to validate the proposed model more data are needed from experiments that take place for longer periods of time. In this study, only the fence panel presented in section 4 was tested after 5 years. If the above model is applied, the difference between the accelerated environment in which the ageing test coupons were subjected and the mist room environment in which the fence panel were stored is equivalent to 2 logarithmic decades (from the difference in temperature). The MOR retention vs. time (in hour) for the fence panel and the results of 60 °C hot water ageing test premix GRC samples are plotted in double logarithmic scale (Figure 17).

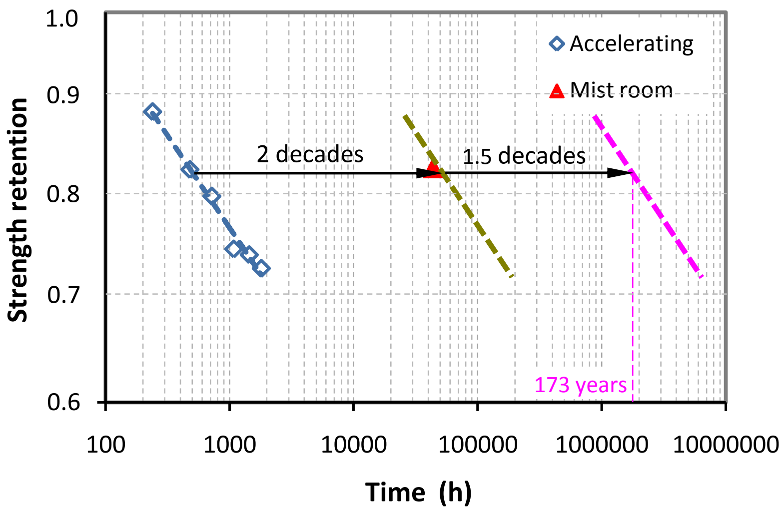


Figure 17 OPC GRC ageing performance

As can be seen in Figure 17, the prediction of the model agrees very well with the test results from the panel. The difference between the mist room condition and the natural environment in the UK is 1.5 logarithmic decades (1 from the difference in moisture condition and 0.5 from temperature). This means that if the panel was exposed to the UK environment it would have taken 173 years for the strength to drop to the value of 0.86 of MOR.

6 Conclusion

By modifying the matrix with VCAS pozzolan, the GRC strength and ductility reduction was lessened. The further addition of acrylic polymers showed only a marginal effect on the ageing process. The glass mesh reinforced GRC showed good durability with the strength retention being above 50% after 75 days of ageing. The ageing performance of GRC containing VCAS pozzolan or acrylic polymer was found not to agree with the Litherland et al. ageing model well. Pure OPC premix GRC or OPC premix GRC reinforced with glass fibre mesh deteriorate in a similar way as those used to formulate the above model.

A durability model based on the study of FRP reinforcement in concrete was adapted. By applying various ageing condition terms, data from accelerated ageing tests can be correlated to the natural weathering condition and consequently to predict the service life. The limited test data from this study fit in the model well. Clearly more tests need to be done to verify this model.

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