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Mechanical Behaviour of Cementitious Matrix Composites

A. G. Magalhães,[a] A. T. Marques,[a] F. M. F. Oliveira,[a] P. Soukatchoff[b] & P. T. de Castro[a]

[a] INEGI — Instituto de Engenharia Mecânica e Gestão Industrial, Porto, Portugal
[b] Pont-a-Mousson S.A.-D.D.P.P., Pont-a-Mousson, France

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Abstract

This paper presents the experimental work on the fatigue, impact and creep behaviour of cement matrix composites developed in the context of a project seeking the development of a composite with improved ageing characteristics. The experimental techniques used, as well as equipment specifically designed for some of the tests are described. The performance of the materials tested, after 28 days as well as artificially aged in water for 84 days at 50°C is presented and discussed.

INTRODUCTION

Glass fibres are mixed in Portland cement matrices without taking into account the problem of chemical and physical compatibility of the glass with the matrix. This leads to a dramatic reduction of the ultimate strength and strain of the glass-reinforced cements after ageing. Indeed, the glass is attacked by the alkalinity and the lime of hydrated Portland cement.[1] Two processes using glass fibres in cementitious matrices are currently available: GRC (Glass-Reinforced-Cement) uses an alkali-resistant glass fibre and PGRC (Polymer Glass-Reinforced Cement) uses an E glass fibre in a cementitious matrix modified by an acrylic polymer.[2,3] The present study on the mechanical behaviour of cement matrix composites concerns 4 materials — after 24 h in covered mould and 27 days at 20°C, 50% RH and aged in water for 84 days at 50°C — subjected to fatigue, impact and creep testing.

In many situations a component may be subjected, in service, to dynamic loading, displaying less resistance than under static loading. This phenomenon, known as fatigue, is often described by curves of stress range versus number of cycles, and frequently an asymptotic behaviour defines the fatigue limit. Many metallic materials display a fatigue limit, but other materials, such as concrete, do not have that property in the usual sense. Therefore their resistance is defined for a given number of cycles — for example 10^6.[4] For reinforced concrete, fatigue loaded for this number of cycles, the resistance will be of the order of 60 to 70% of the value for static loading.[5] Extensive experimental fatigue studies have been conducted on steel fibre reinforced mortar and concrete beams.[5–8] The fatigue process consists of the successive accumulation of damage, inducing the loss of strength of the material. For homogeneous and isotropic materials the damage is associated with the initiation and propagation of a crack until final rupture occurs. For very heterogeneous materials, such as concrete, that concept of damage is meaningless, since, in this case, the simultaneous propagation of several cracks, together with the sliding and accommodation of the constituents is possible. This microstructural damage process may, eventually, not even lead to final rupture or to visible damage. When loaded under constant stress range, which corresponds to the usual fatigue testing, the great accommodation capacity leads to high displacement amplitudes,[9] and this is often conducive to very unstable tests. When the cyclic loading consists of a constant displacement range, the initial force or stress range decreases with number of cycles; although this is not a conventional fatigue test leading to SN curves, the load or stress range drop is associated with the decrease in mechanical strength and with the accommodation of the fibre and matrix constituents. The behaviour under impact loading is of great significance for the understanding of the mechanical behaviour of materials. The phenomenon is produced by an impulse excitation, which varies according to a law defined by a physical variable (force, acceleration, etc.) which is a function of time.[9] The impulse and its evolution in time may be measured by a sensor associated with the striker and recorded, for example, on a digital oscilloscope. From $F=M(\mathrm{d}v/\mathrm{d}t)$, where F is force, M is striker mass, $\mathrm{d}v/\mathrm{d}t$ is the derivative of speed with time, the integration will give the speed versus time relationship. A second numerical integration gives the displacement–time relationship, and finally the force–displacement curve may be obtained.[10] The interpretation of the result of an impact test critically depends upon the data collecting procedures used. According to Matthew *et al.*,[11] it is essential to pay attention to the following parameters of the circuit (instrumentation plus mechanical device): trigger procedure, striker mass, amplifier gain, filtering, force and time amplitude. Other factors, external to the circuit, such as inertial forces whose amplitude is proportional to the impact speed, and harmonic oscillations resulting from the excitation of natural frequencies of specimen and striker, may have a direct influence upon the result. The solution requires the use of low impact speed and the use of adequate filters.[12] The multiphase nature of concrete implies out-of-phase mechanical responses among the constituents, as well as the distribution of granulates and their relative stiffness, porosity and its distribution, and the different cracking modes.[9] These factors justify the larger scatter of dynamic tests, when compared with the scatter of static tests.

Under constant loading, materials present time dependent non-linear strain–creep, which depends upon microstructural phenomena. Some materials, such as steels, only display this behaviour at considerably high temperatures, but others, such as polymers, display this behaviour at room temperature as a consequence of their viscoelastic nature. The analysis of creep behaviour displayed by concrete is considerably more complex than that of the mentioned materials. Concrete is an heterogeneous material, with a metastable matrix which undergoes continuous changes as a result of hydration reactions, of water transfer mechanisms, of volume contraction, of microcracking and development of porosity. The multiphase nature justifies two types of behaviour:[13] linear elastic behaviour associated with most aggregates, which does not directly contribute to creep but contributes to internal stress distribution, and viscoelastic behaviour associated with the remaining matrix. Creep mechanisms are divided into two groups: short term and long term. The first are explained by stresses induced by water redistribution in the matrix. Long term creep mechanisms are more complex. The hydration products, when dry, constitute a compact system and all particles are compressed by their surface tension. This porous system may interact with water, leading to a local increase in volume. Some particles, kept in their original location by primary connections may, under creep, leave their initial locations.[14] Adding fibres does not seem to influence the process, due to their low percentage in the composite. Creep strain is proportional to, and is usually presented as a function of, initial strain.[15,16] Creep strains are lower than those caused by dilatation or volumetric contraction corresponding to matrix changes, which are frequently considered together with creep phenomena.[13]

MATERIALS

The experimental programme concerns two reinforcement types: glass fibres and cast steel ribbons. Three glass fibre reinforced materials were tested: GRC(28), a composite of alkali resistant (AR) 38 mm long fibres in a Portland cement matrix, after a cure of 28 days (24 h in covered mould and 27 days at 20°C, 50% RH); GRMC(28), a composite of alkali resistant (AR) 38 mm long fibres in a Portland cement matrix modified with the addition of a pozzalana, after a cure of 28 days (24 h in covered mould and 27 days at 20°C, 50% RH); PGRMM(28), a composite of alkali resistant (AR) 38 mm long fibres in a Portland cement matrix modified with the addition of a pozzalana and of an acrylic polymer, and also materials GRC(84), GRMC(84) and PGRMM(84), similar to the foregoing but sub-

Table 1. Mixes used in the experimental programme

	GRC	*GRMC*	*PGRMC*
Cement CPJ	100	100	100
Sand	70	70	70
MK E1	0	25	25
Latex dry 100% polymer*	0	0	6·15
water (+ water from Latex)	38	45	47
Superplasticizer	0·8	2·5	1·5
AR glass Fibres(%)**	5	5	5

*Based on mortar volume.
**Based on mortar weight.

jected to artificial ageing consisting of immersion in water for 84 days at 50°C. Table 1 gives the mixes used.

The mineralogical composition of the CPJ cement was given by quantitative analysis by X-ray powder diffraction and is given in Table 2. The qualitative analysis of the pozzalana MK E1 gives Muscovite Mica, Quartz (SiO_2) and Cristabalite (SiO_2). Cast steel ribbon reinforcements were used in Type 55 Portland cement matrices, natural silica sand (0–3 mm), along with two types of aggregates: crushed gravel (6–10 mm) and natural aggregates (5–10 mm). Four different volume percentages of reinforcement were used: 0%, 0·4%, 1% and 1·6%. Fibres were 30 mm long, 1·6 mm wide and were randomly dispersed in the matrix.

FATIGUE TESTING

For given initial maximum and minimum values of load (or stress), and using constant displacement tests, the damage was measured as a function of number of cycles; the criterion for damage measurement was the load or stress range drop as a function of the number of cycles, for each initial load (stress) range. Measurements of number of cycles corresponding to 5, 10 and 20% drops were recorded. As a complement to the damage assessment, and for the case of glass fibre reinforced materials, the elasticity modulus before and after tests, consisting of 10^6 cycles, was measured. All tests were performed with an initial value of $R=P_{min}/P_{max}=0{\cdot}1$.

Testing equipment

A bending test machine for displacement controlled tests was designed and built (Fig. 1). It performs three- or four-point bend cyclic tests on beam specimens of rectangular cross section, at 10 Hz frequency. The specimen is supported by two load transducers of 2 kN capacity, which may be displaced on a rectified table in order to set up the loading span. The displacement amplitude is set up using a cam consisting of eccentric rings; a bearing controls the actual loading device. The specimen is set up in the testing machine by lifting or descending the rectified table using a screw and wheel mechanism.[12] This machine is an evolution from one produced by Oliveira[17] to perform fatigue cracks on CTOD (Crack Type Openning Displacement) specimens.

The loading sinusoid was defined from discrete data acquisition controlled by software. For the loading of Fig. 2, for example, if a sufficiently large number of random data points is recorded, the evolution of the amplitude of the sinusoid during the test may be measured. For this purpose a sampling of some maximum and minimum values and their averages were recorded. Those mean values, and the corresponding time (or number of cycles) were recorded for subsequent treatment.

Specimen preparation

The glass fibre reinforced composite specimens were obtained from panels made by simultaneous projection of matrix and short fibres randomly distributed. The specimens with $220 \times 50 \times 10\ mm^3$ were packed, after cure, in plastic bags until testing. The cast steel ribbon specimens were cut from plates made by manual mixture of the matrix and fibres. They were $350 \times 80 \times 20\ mm^3$ and were kept until testing without any special conditioning.

Table 2. CPJ cement composition

Alite	*Belite*	*C3A*	*Ferrite*	*Calcite*	*Hemi-hydrate*	*Anhydrite*	*Portlandite*	*Dolomite*
57%	14%	3%	1%	17%	1·5%	1·5%	3%	0·5%

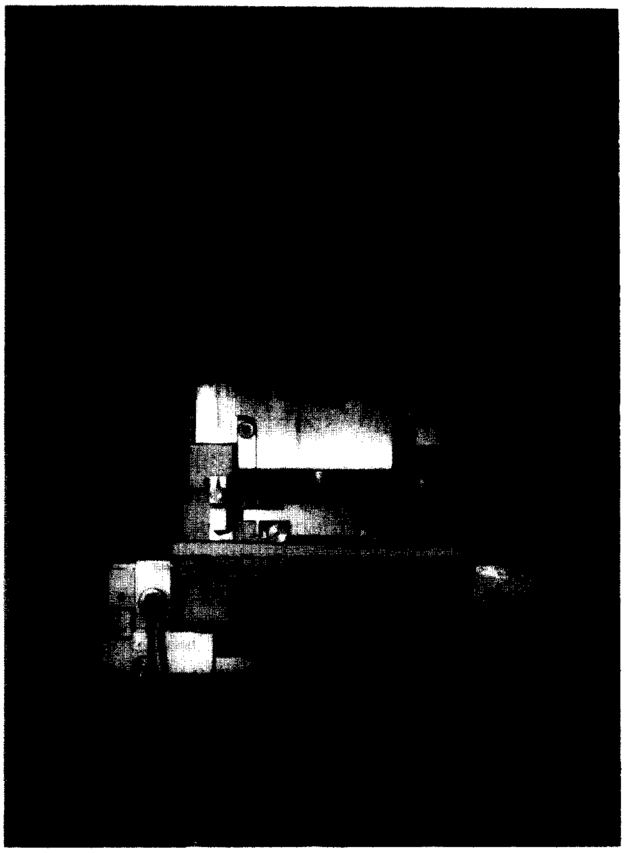


Fig. 1. Displacement control fatigue machine.

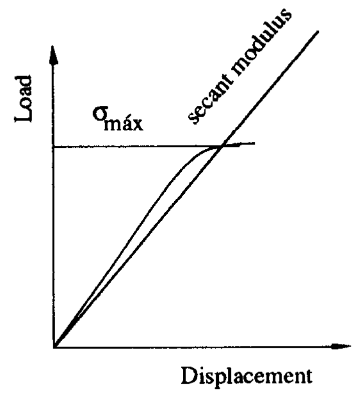


Fig. 3. Secant modulus.

Secant modulus — glass fibre specimens

The measurement of the fatigue loading dependence on the elasticity modulus was carried out at 20°C on three-point bend specimens tested before and after 10^6 cycles.[16] Although the three-point bend test is not a standard procedure to measure the modulus, it was used because of its simplicity as a comparative process to measure the material behaviour before and after the fatigue test. The modulus was defined for this purpose as the secant through the maximum stress level in the beginning of the fatigue test (Fig. 3).

As auxiliary equipment an inductive LVDT transducer and a signal conditioner were used. The specimens were loaded and the displacement at the middle point was measured. For each load level, 5 or more specimens were used. The data obtained for the 4 loadings corresponding to 5, 7, 10, 12 MPa and the best fit correlation for each case, are presented in Fig. 4. A comparative analysis of the drop in modulus for each case shows that artificially aged materials display a smaller reduction of secant modulus.

In the elastic range, as in this case, the modulus is mainly dependent on the matrix composition and on the temperature. As we can see, PGRMM composites present a small modulus. As shown by the increasing polymer content the deformation capacity of PGRMM increases and the elasticity modulus decreases.[18]

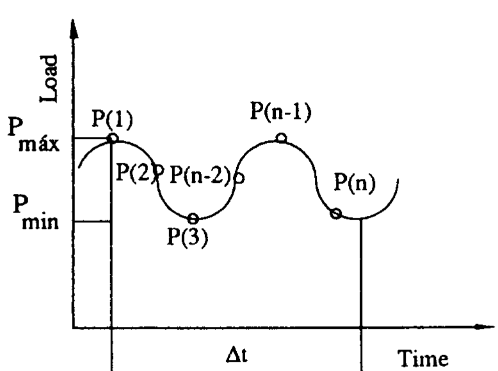


Fig. 2. Load amplitude acquisition.

Stress evolution — glass fibre specimens

The stress amplitude $\sigma_{max}-\sigma_{min}$ displays a rapid decrease at the beginning of the test, due to the accommodation of the matrix and reinforcements, and converges to an asymptote after 200 000 to 250 000 cycles, as illustrated in Fig. 5 for the GRC(28) material, where a logarithmic fit of the form $\Delta\sigma = a - b\log N$ corresponding to the average of 5 tests at each stress level is presented.

A comparison of the behaviour of several materials, in Fig. 6, shows that the stress range drop in percentage is less noticeable in the case of the artificially aged materials. The GRMC and PGRMM composites presented a tendency for smaller drop during cyclic loading. This fact is suggested by a greater number of cycles for the same degradation level.

The testing programme leads to the following conclusions:

considerable scatter was found, a situation to be expected when testing these materials,

the materials do not display visible macroscopic damage when subjected to this type of loading,

artificially aged materials suffer less damage (measured by the drop in stress range (σ_{max}-$-\sigma_{min}$) than corresponding non-aged materials,

damage (measured by the drop in stress range $\sigma_{max}-\sigma_{min}$) occurs very quickly in the initial moments of the test,

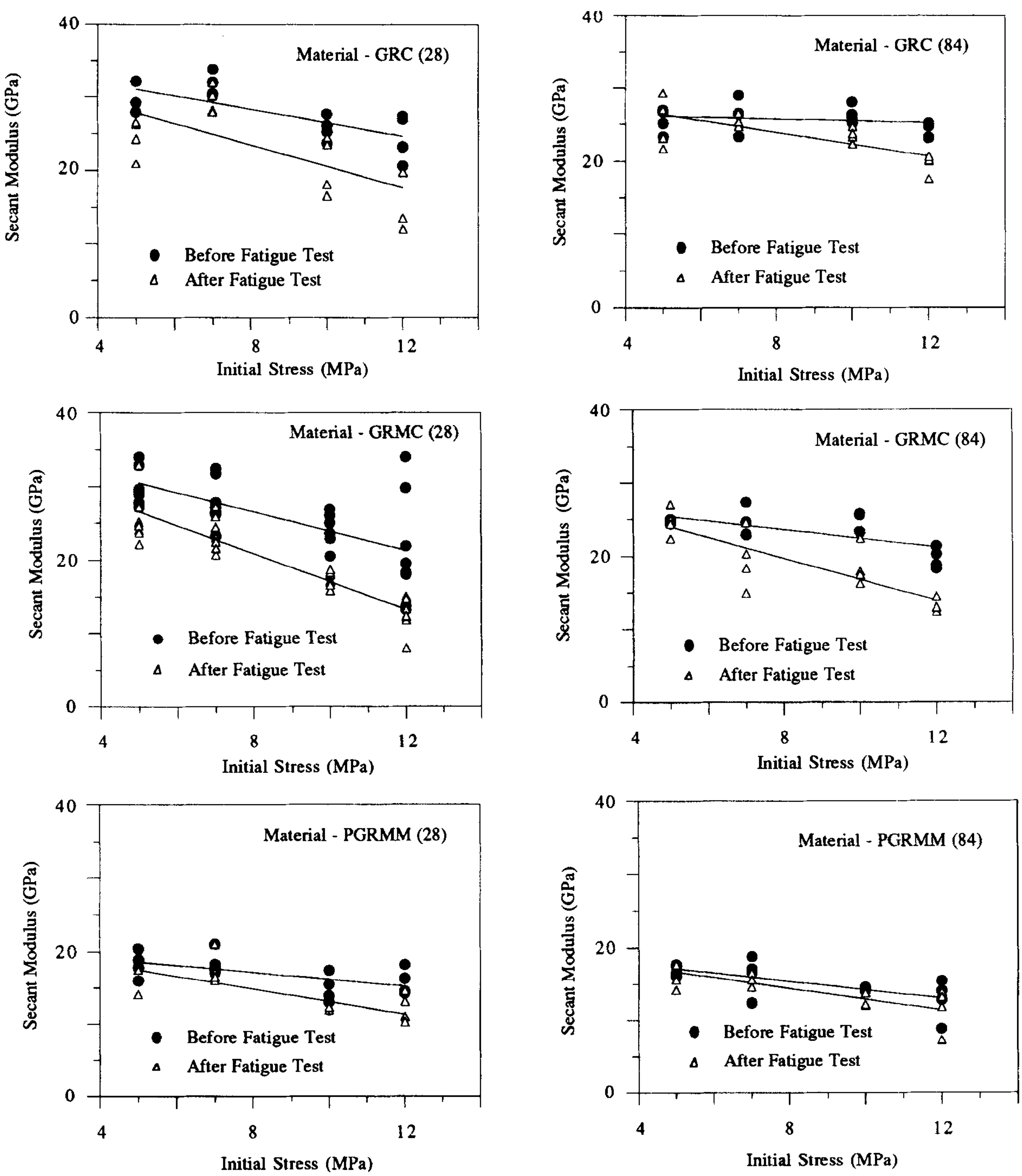
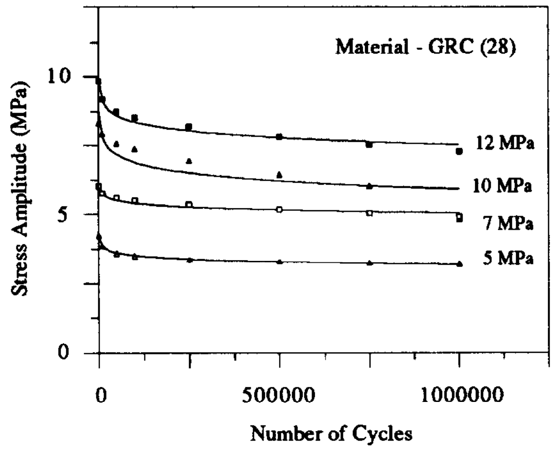


Fig. 4. Modulus degradation in fatigue conditions.



σ(MPa)	a	b	R
12	12.0	0.8	0.98
10	11.2	0.9	0.87
7	6.9	0.3	0.97
5	5.0	0.3	0.99

note:R is the best fit correlation factor

Fig. 5. Stress amplitude versus number of cycles for GRC(28) material.

for all tests a *plateau* was found in the region 200 000 to 250 000 cycles, and corresponds to stress range drops of the order of, or greater than, 20%.

In general, the greater matrix stability has a favourable effect on time-dependent properties. The space between the fibres and the matrix increases on ageing of the product because the voids between individual filaments of the fibre bundles are gradually filled up with cement hydration products.[19] The matrix becames more brittle, but also more compact. The greater compactness gives improved fatigue resistance, both as regards initiation as well as crack growth. The observed damage takes place

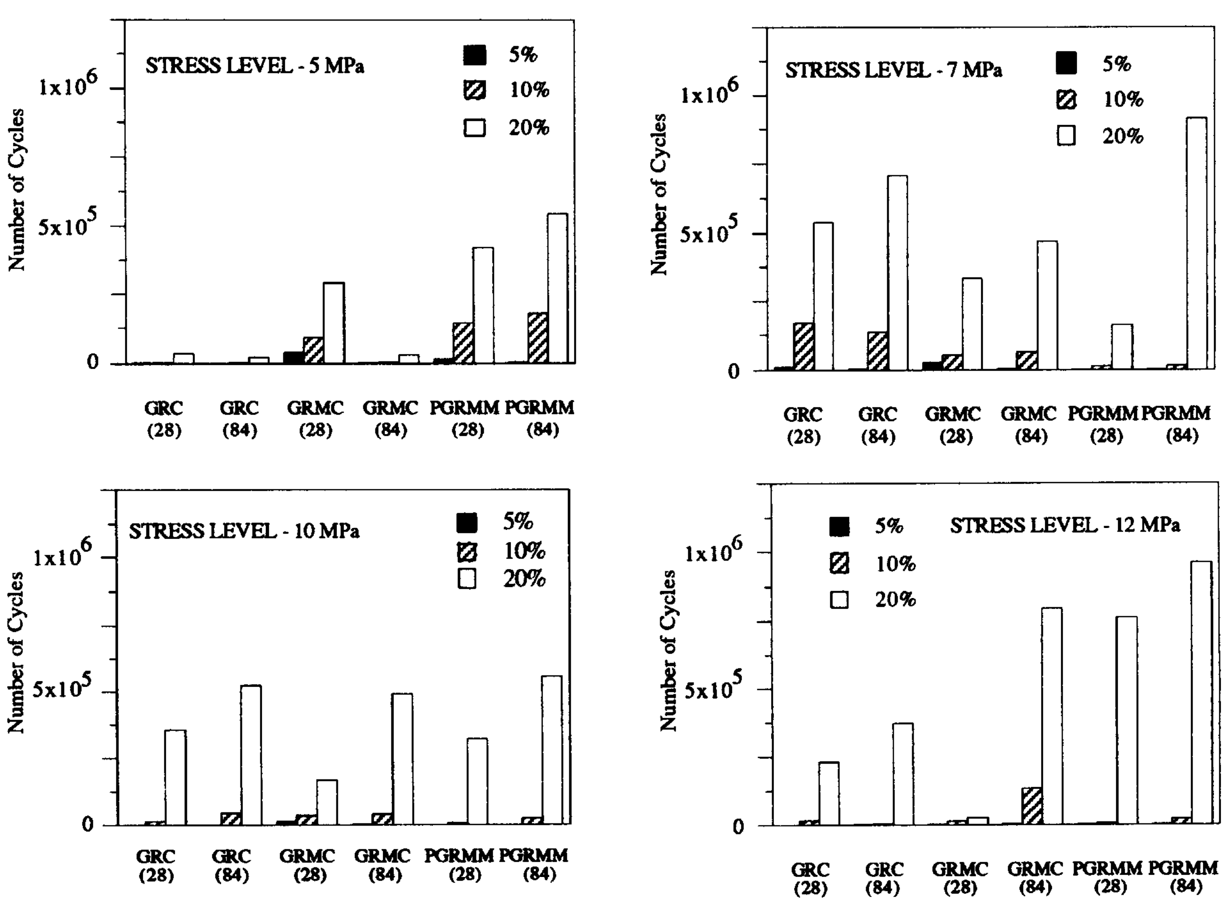


Fig. 6. Degradation during cyclic loading.

mainly in the initial phase, and is the result of the accomodation of constituents, which is the reason why it is not observed macroscopically.

Stress evolution — cast steel ribbon specimens

For each weight percentage reinforcement 4 levels of initial stress — 35, 45, 60, and 80% of rupture strength (as measured in a static test) were used. Generally, the stress range decreases very quickly, see Fig. 7.

For the initial maximum stress of 10 MPa, or greater, some ruptures during the test were observed.[20] In those cases where there was no rupture during the cyclic loading, consisting of 10^6 cycles, the percentage of range drop versus number of cycles of the cast steel ribbon reinforced matrices was plotted, Fig. 8.

A larger weight percentage of fibres in the matrix does not correspond to an improvement of the resistance to cyclic loading. This fact is more obvious for the greater stress levels. In this comparison it is shown that the composite with 0·4% fibre content displays the best overall performance as regards the drop in stress range during the test.

From the cyclic tests carried out on cast steel ribbon reinforced cementitious matrix composites the following conclusions resulted:

scatter found for these tests was considerable, generally, neither fatigue rupture nor visible damage was found,

a large weight percentage of the fibres degrades the cyclic loading resistance of these materials,

of the materials tested, the 0·4% fibre weight percent displays the best overall performance as regards the drop in stress range during the test.

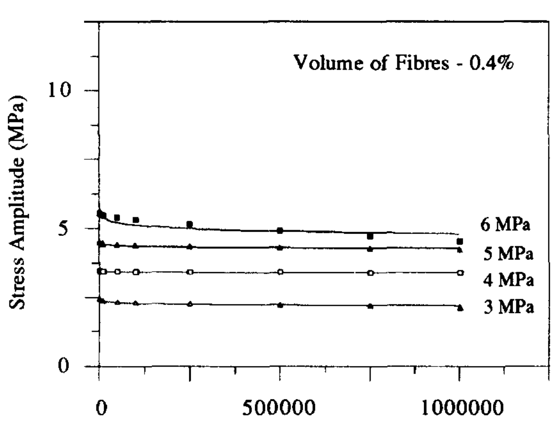
For a given mix, the fibre geometry is very important to the properties of the fibre reinforced concrete.[21] The shape of the cast steel ribbon favours the initiation and the growth of matrix microcracking. Fatigue strength is therefore decreased. On the other hand, a large fibre content reduces workability, and the formation of voids is likely. In this case, the matrix accomodation causes a fast decrease of the initial stress range. Matrix compaction has an important role regarding the properties of cement and concrete products.[22] The accomodation effect resulting from fibre content is easily seen for 45% of MOR. Whereas for fibre content of 0·4% the damage after 10^6 cycles is low (5%), for fibre contents of 1 and 1·6%, 10% damage occurs after half that number of cycles. In both cases a tendency for stabilisation is found after 10^6 cycles.

IMPACT

Testing equipment

Impact tests on glass fibre reinforced specimens were conducted on a Charpy pendulum, with a maximum available energy of 300 J. Drop height was selected in order to obtain impact speeds of 3 and 1 m/s, corresponding to maximum energies of 122 and 13·6 J, respectively. The circuit shown in Fig. 9 included the following equipment:

a resistive type accelerometer with 0·5 mV/V sensitivity;



σ(MPa)	a	b	R
6	6.4	0.30	0.87
5	4.6	0.08	0.94
4	3.4	0.02	0.95
3	2.7	0.10	0.96

Note: R is the best fit correlation factor

Fig. 7. Stress amplitude versus number of cycles for $V_f = 0{\cdot}4\%$.

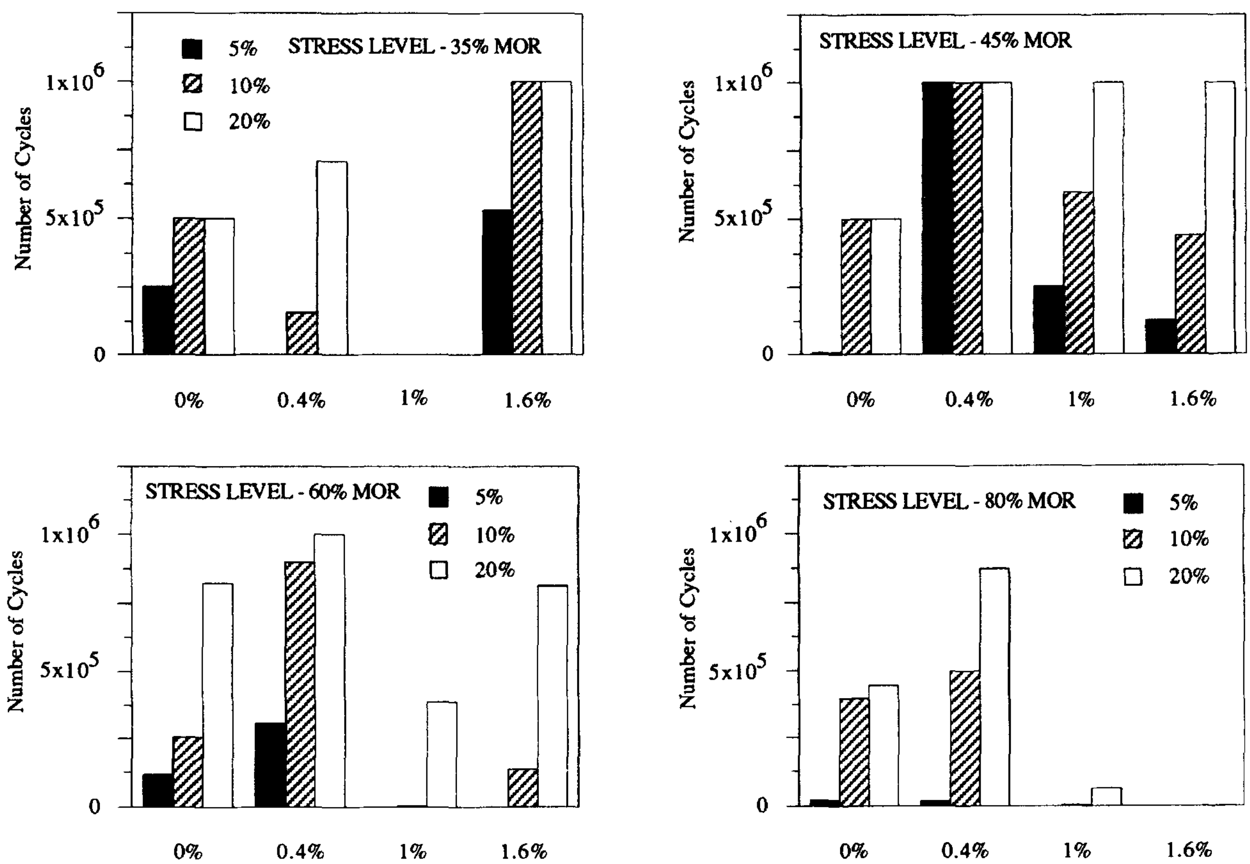


Fig. 8. Degradation level for cast steel ribbon reinforced matrices.

one digital oscilloscope, with sampling frequency of 5 μs per point;
one instrumentation bridge, as power supply (2 V) for the accelerometer and signal amplifier (10 000 X);
one filter.

Data was recorded on the oscilloscope, using diskettes, and treated on a microcomputer using software developed for this purpose.

Tests on cast steel ribbon specimens were carried out using a pendulum with a different specimen support. An electronic chain similar to that already described was used.

Specimen preparation

The glass fibre reinforced specimens were cut from plates, to their nominal dimensions of $100 \times 10 \times 10$ mm^3. After cutting, the specimens were packed in sealed bags, to be reopened only for the testing. Cast steel ribbon specimens were of nominal dimensions $200 \times 60 \times 20$ mm^3.

Impact speed and temperature effects — glass fibre specimens

The testing programme with these materials looked at the influence of two parameters: test

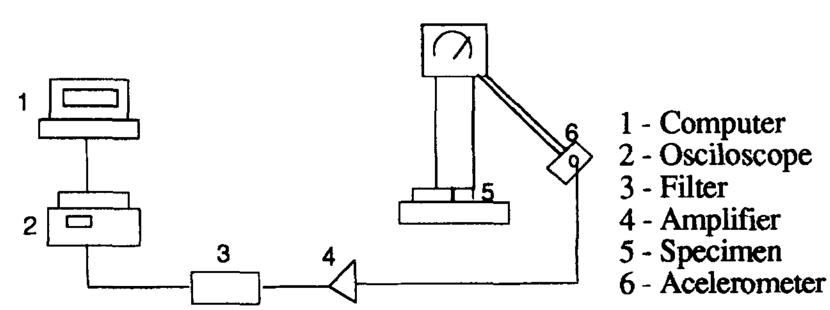


Fig. 9. Circuit for signal generation and recording in an impact test.

speed and temperature. In order to determine the influence of test speed, room temperature tests at 1 and 3 m/s were carried out. Data obtained show that in the range tested there is no influence of speed. All further testing was carried out at 1 m/s. Fig. 10 presents a synthesis of the data obtained with 5 specimens for each case.

In order to study the possible temperature dependence, specimens were conditioned in an oven, cooled by flow of carbon dioxide at 0, −20, −40 and −60°C, respectively, during a time interval long enough to make sure that perfect thermal stability was attained. Figure 11 presents the data obtained with non-aged materials.

A synthesis of data obtained with glass reinforced specimens shows that:

artificial ageing leads to an important decrease in toughness;

matrix modification, adding pozzalanas, or a polymer, prevents the sharp decrease in toughness with ageing;

absorbed energy is not noticeably influenced by initial test speed (in the range of speeds tested here);

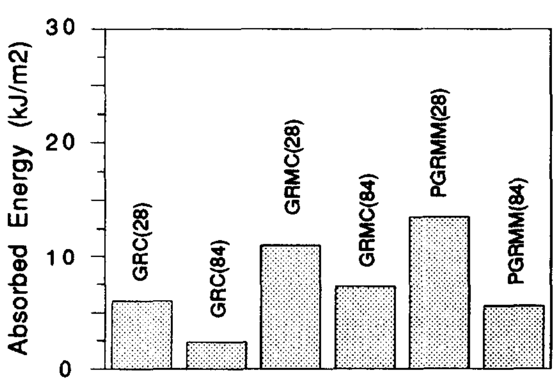


Fig. 10. Impact test data: glas fibre reinforced materials.

absorbed energy is temperature independent between −60 and 20°C. A large scatter was however noticed, which may result from a specimen size too small to reflect the behaviour of the material or a large matrix heterogeneity.

If the initial favourable properties of GRC are to be retained we must prevent the formation of a hard interfilament layer. Bijen[23] showed that a solution to solve this problem was found by adding a polymer which fills up the interfilament spaces and is capable of chemically binding Ca^{2+}. In fact, the PGRMM material presents a high impact strength, but when aged, the impact strength falls to a level not much better than that of GRC. Mineral modification also gives good behaviour. On reducing the formation of $Ca(OH)_2$ the matrix becomes more ductile, improving impact strength. This was also observed in Ref. 1 for GRC with AR glass fibres. The scatter found is typical of these dynamic tests. The small specimen size also contributes to the scatter, since this specimen does not display the real global behaviour of the composite fibre–matrix. This fact was mentioned by Johnston[24] when discussing impact testing on 22 × 22 × 100 specimens, which are considered too small.

Cast steel fibre specimens

These tests were carried out at room temperature, using a pendulum of 300 J maximum available energy, with initial test speed of 5 m/s. Energy absorbed for each one of the formulations (0, 0·4, 1 and 1·6% volume fibres) is presented, as an average of 5 specimens in Fig. 12.

For the cast steel ribbon reinforced materials the following conclusions were derived:

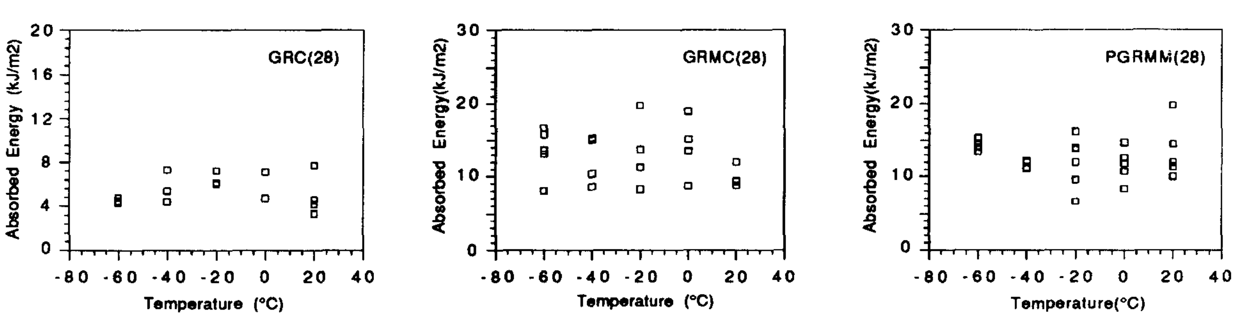


Fig. 11. Behaviour of non aged materials with temperature.

increase in volume percentage of fibres improves toughness;

there is a small increase in absorbed energy when fibre percentage increases from 1 to 1·6%, suggesting a stabilisation for these levels of reinforcement.

Fibres in a brittle matrix strongly contribute to energy absorption.[24–28] Romualdi and Mandel[29] showed that the improved strength is due to the delayed appearance of a first crack. Once the matrix cracking initiates, and friction between fibre and matrix during pull-out occurs, toughness depends upon load transfer mechanisms. A high loading rate stresses this effect.[30]

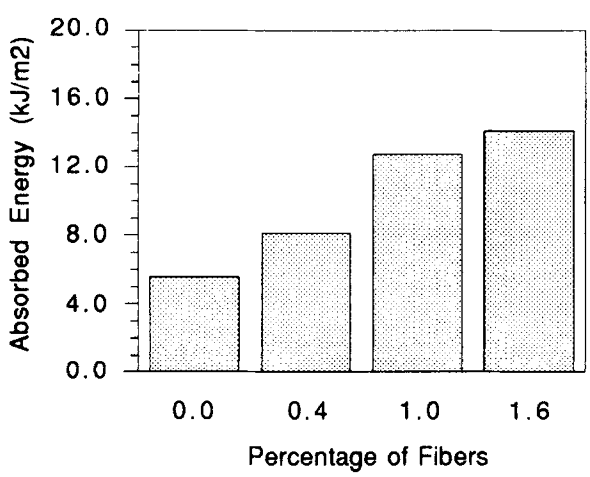


Fig. 12. Absorbed energy; cast steel ribbon reinforced materials.

CREEP

Testing equipment

Creep testing on glass fibre reinforced specimens was carried out at room temperature (immersed in water), using four-point bending as shown in Fig. 13.

In order to keep the water temperature constant, two 75 W electric resistances were used. Time dependent strain was determined from a record of mid span displacement, obtained with a mechanical gauge of 1 μm resolution.

Specimen preparation

Glass fibre specimens were parallelepipeds with nominal dimensions $220 \times 50 \times 10$ mm^3. Testing corresponding to cast steel ribbon reinforced materials took place at room temperature in a device similar to the one shown in Fig. 13. The cast steel ribbon specimens were parallelepipeds of nominal dimensions $350 \times 80 \times 20$ mm^3.

Creep strain — glass fibre specimens

These tests were conducted at room temperature (20°C) and in water (22°C). Before testing in water, all specimens were weighed, and immersed for 24 h. After this, specimens were again weighed, and no change in weight greater

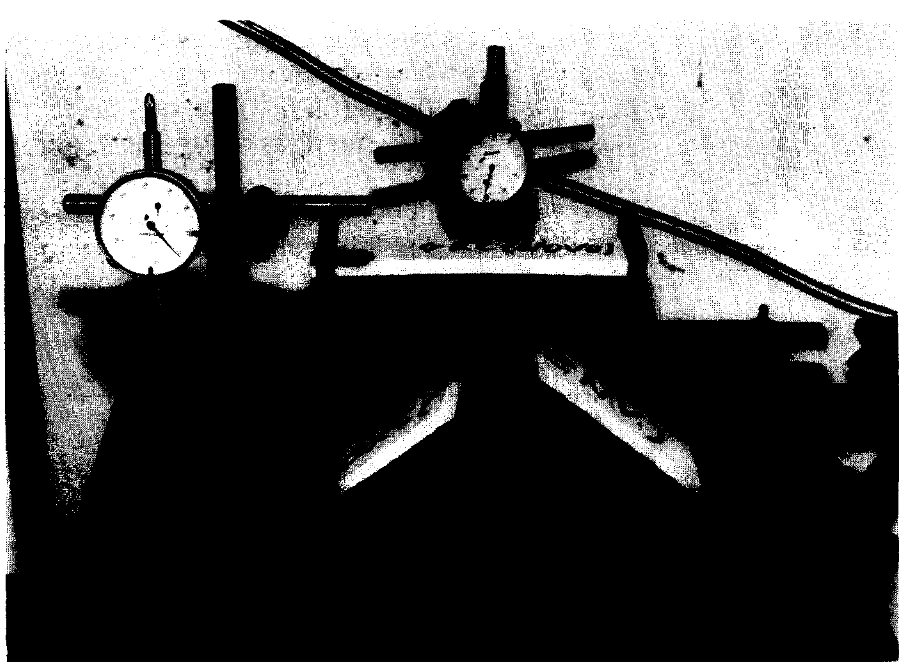


Fig. 13. Four-point bending rig for room temperature test.

than 4 g was recorded. This reveals the low permeability of these materials. Periodically, water was added in order to compensate for loss due to evaporation. The initial testing conditions were 10 MPa. Results obtained are shown on log–log plots in Fig. 14.

Creep testing on GRC, GRMC and PGRMM composites, in air at room temperature and immersed in water, shows that these materials are influenced by hygroscopic conditions. On GRC and GRMC it was shown that a large percentage of creep strain takes place at the beginning of the test.[31] In general, the creep was higher when the specimens were immersed. The exception was PGRMM. The presence of the polymer decreases the matrix permeability and the filling of the interfilament spaces between glass fibres and coating of glass fibres by polymer also decreases the structural modifications in the matrix. When these materials are under weathering conditions or immersed they are able to maintain their creep properties to a greater extent. Some creep studies indicate that creep properties are controlled largely by

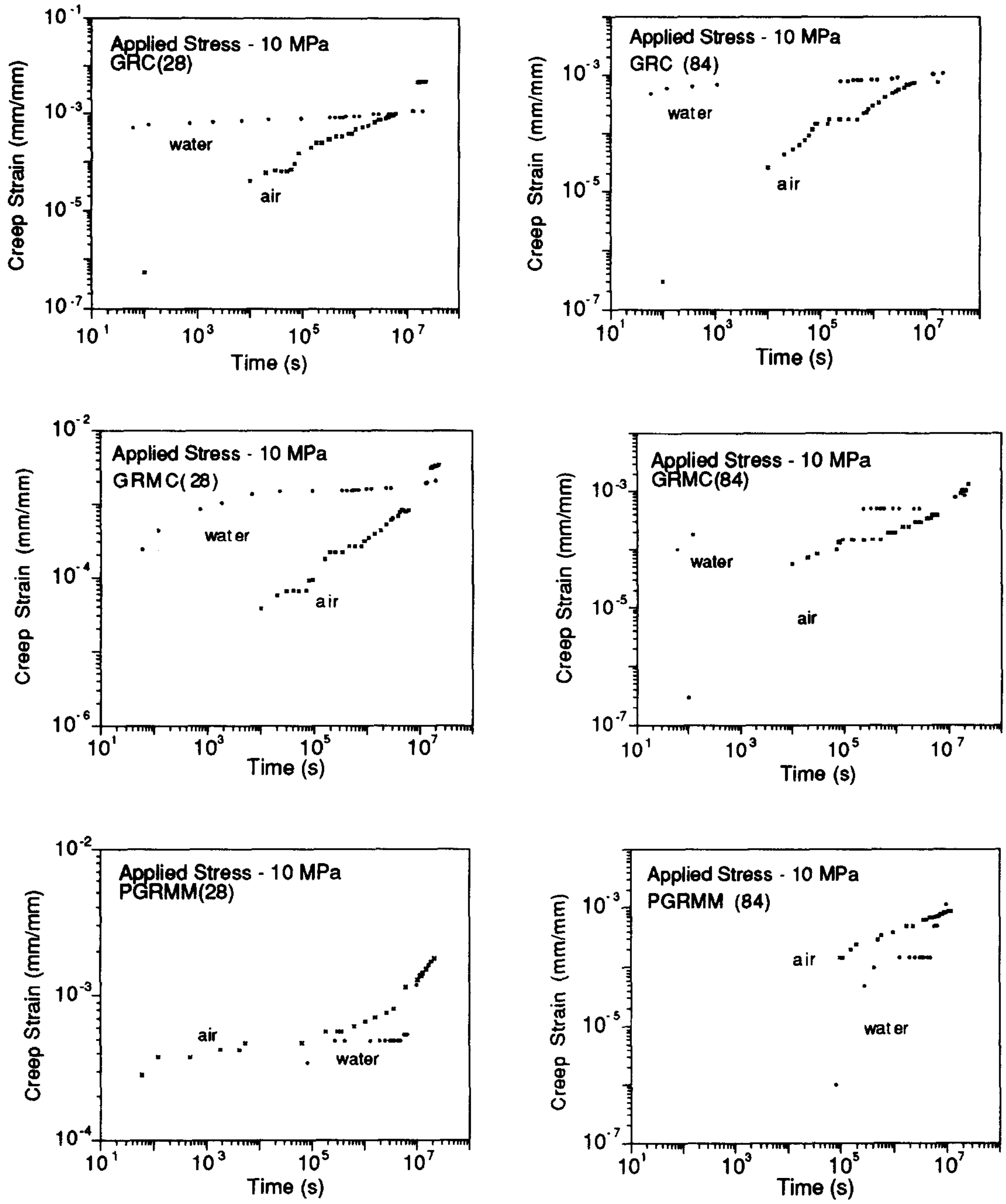


Fig. 14. Creep results for glass fibre specimens.

the matrix. This is expected because of the small proportions of the fibre in the composite (5% by weight).[31]

Creep strain — cast steel fibre specimens

Testing was conducted at 30, 60 and 90% of rupture stress. Unreinforced matrices (*Vf*=0%) display, generally, premature ruptures, whereas for other *Vf* values multiple cracking was found. This multiple cracking, more noticeable for the less reinforced matrices, leads in some cases to ruptures. For *Vf*=1·6% this effect, although it exists, is not macroscopically visible. Figure 15 shows the behaviour corresponding to 90% rupture stress.

For 60% rupture stress creep strain was observed for 1 and 1·6% reinforcements (Fig. 16). Due to the low strain levels, testing at 30% rupture stress was discontinued.

Tests on cast steel ribbon reinforced materials showed that the fibres improve the creep behaviour of the material, particularly preventing catastrophic ruptures. Instead of catastrophic rupture, a multiple cracking behaviour is found in the presence of fibres. This behaviour is more marked with higher fibre percentages. It was possible to see that the fibres bridged the cracks and that one effect of fibre–matrix friction might occur. For low strain levels this behaviour is not so marked because the presence of cracks is not so important for the same testing time.

CONCLUSIONS

Matrix modification with pozzalanas or with a polymer improves markedly impact strength. This modification also improves fatigue resistance. Ageing, detrimental as far as toughness is concerned, does not seem to influence creep and fatigue behaviour. This fact supports the conclusion that matrix stability has favourable consequences as far as time dependent behaviour is concerned. The damage process cannot be macroscopically observed, and in some cases scatter was notorious. From a mechanical point of view, the mixing stage may be crucial, since homogeneity will reduce behaviour scatter.

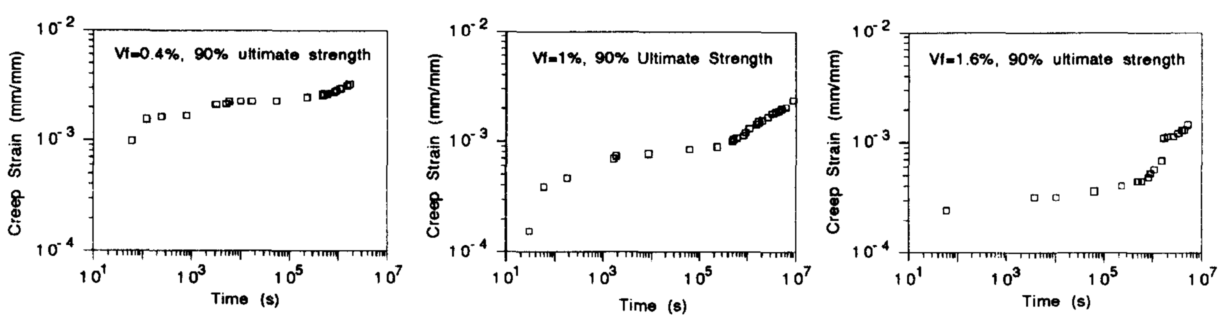


Fig. 15. Strain–time plot for 90% rupture stress.

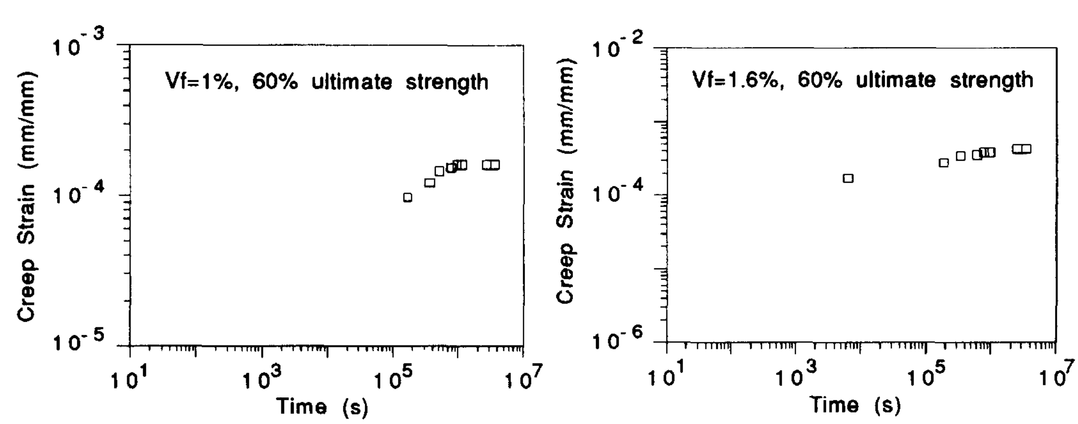


Fig. 16. Creep strain–time plot for 60% rupture stress.

Cast steel ribbons give an overall positive contribution to mechanical behaviour. Under constant loading, during long periods, they induce a multiple cracking mechanism, of slow development, leading to an improvement in life and particularly preventing catastrophic rupture. Toughness improves markedly — $Vf=1\%$ almost doubles the impact absorbed energy. This improvement is not, however, proportional to fibre volume percentage — it was found that there is a trend to stabilisation when Vf is greater than 1%. Damage under fatigue loading is fast, although not observable macroscopically. When fibre percentage increases, strength under cyclic conditions decreases, particularly when applied stress is near to rupture stress.

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