TEMPERATURE AND ENVIRONMENTAL EFFECTS ON GLASS FIBRE REBAR: MODULUS, STRENGTH AND INTERFACIAL BOND STRENGTH WITH CONCRETE

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ABSTRACT

In general, it is expected that concrete structures using glass fibre reinforced plastic (GFRP) rebar as reinforcement could have improved durability compared to normal steel reinforcement because of corrosion resistance of the rebar. However, there are some aspects of the behaviour of the GFRP bars under temperature and high alkali test conditions which must be explored. This paper considers the effects of water and alkaline environments on the bond strength between the concrete and the rebar and strength and stiffness of the GFRP rebars at a range of different temperatures (20 to 120°C). The three types of GFRP rods investigated in this work were subjected to alkaline solutions at 60°C for three different exposure times i.e. 30 days, 120 days and 240 days. Tensile tests were carried out for physical-mechanical characterisation on the exposed rebar specimens. The aim of the study is to identify degradation processes and to show how accelerated ageing regimens can be used to differentiate between different GFRP rebar products in terms of durability. The results obtained from this work provide a base-line set of data which can be used in the future in conjunction with the thermal properties of the material to facilitate the modelling of the long-term properties of composite reinforced concrete structures at elevated temperatures. This will be particularly useful in the prediction of the performance of GFRP rebar reinforced concrete structures subject to fire

KEYWORDS: A polymer matrix composites (PMC's), glass fibres, B environmental degradation, D mechanical testing

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1. INTRODUCTION

The use of a composite reinforcing bar for concrete as an alternative to traditional steel reinforcing bar has many potential advantages. The material is relatively light and corrosion resistant. The long term cost of ownership of structures based on composite rebar may be significantly less than that of steel reinforced structures even if the initial capital costs are increased. A rigorous financial assessment of the value of using this alternative material must, however, have representative data on the long term durability of concrete reinforced with composite rebar and must be able to assess the performance of the structures under non - standard conditions which have to be considered in the design and regulation process. Composite rebars are usually based on glass fibre reinforcement which, in some forms, is known to be degraded by alkaline environments, Takewaka et al. 1997[1], Micelli et al. 2001[2]. Furthermore, the composite is typically produced with a thermosetting polymer matrix, which has mechanical properties that are seriously compromised at elevated temperatures. An assessment of the durability of a composite rebar reinforced structure must take into account the long term effects of moisture and alkaline environment on the rebar itself and on the interface between rebar and concrete, and must simultaneously feed this data into an assessment made of the properties of the structure in fire situations. Many building structures must satisfy the requirements of building codes, which relate to the behaviour of those structures in a fire. Fire ratings for buildings refer to the time available in a fire before the structure collapses. The relevant property of the composite rebar is not its flammability or reaction to fire, but rather its ability to continue to sustain loads in an environment of rapidly rising temperatures. The properties of steel at different temperatures are well known as are the thermal properties of the material and this allows the modelling of structures with some

degree of accuracy to predict a time scale for the ultimate loss of structural integrity. Similar data is required for glass fibre reinforced plastic (GFRP) rebar in order for similar calculations to be made. It is possible that despite the well-known disastrous effects of high temperatures on the properties of polymer composites (most polymeric matrices will degrade at temperatures over 200°C) the material will perform well in a fire.

This programme of work has examined the properties of composite rebar over the temperature range of 20 to 120°C, with and without long term exposure to alkaline environments. The alkaline exposure has also been undertaken at elevated temperatures in order to accelerate the effect of any attack that might be forthcoming in the real environment of the concrete medium.

Stiffness and strength properties of the rebar have been measured, as both are considered relevant to the structural integrity of reinforced concrete beams. In addition the interfacial strength between rebar and concrete cubes has been assessed under similar conditions and after similar long-term exposure. The data reported in this paper will be used subsequently in related papers to develop a predictive model for the failure of a composite rebar reinforced beam in a standard fire test.

2. EXPERIMENTAL METHODS AND MATERIAL

a) GFRP Rebars

Three types of composite rebar, identified as G1, G2 and G3, were used in this program. These are shown in Figure 1 and their characteristic properties, as provided by the manufacturers, are listed in Table 1. The G1 rods were supplied by Hughes

Brothers, Inc. and consisted of a helically wrapped unidirectional E-glass fibre core with a matrix of high-grade isophthalic polyester resin and an external sand coating. The G2 rods used were supplied by the same manufacturer and differ only in that the matrix is a vinyl ester resin. The glass contents measured according to ASTM D 2584–68 1985[3] in both G1 and G2 rods were 72-75% by weight. The G3 rod is produced from continuous E-glass fibre with a volume fraction of 60%. The matrix of the G3 rod consisted of a urethane modified vinyl ester with overall volume fraction of 35%. Balance of the composite is made up of short ceramic fibres located in the modular spiral thread into the surface of the bar. The G3 rods trade, name C-bar, were supplied by Marshall Industries Composites, Inc.

b) Concrete

Wherever the composite rebars were used in conjunction with a concrete matrix, the mix composition per m^3 of the concrete was 372 kg of ordinary Portland cement (OPC), 542 kg of sharp sand, 1333 kg of 10mm aggregate and 160 litres of water. This gives a cube compressive strength at 28 days of 40 MPa. A concrete mixer with a maximum capacity of 0.1 m^3 was used for the mixing. The mixing sequence was as follows, first the coarse and the fine aggregates and two thirds of the water were loaded into the mixer and mixed for 1 min to allow for the absorption of the water. Then the cement and the remaining water were added and the concrete was mixed for a further 5 minutes prior to casting.

3. TEST METHOD

3.1. Pull - out Test

Pull - out tests were performed in order to measure the interfacial strength between the rebar and a concrete matrix. The tests were performed on the composite rebars partially encased in a 100mm cube of concrete. The GFRP rods were cut into 400mm lengths. The bonded length was 5 x diameter (ϕ) = 60mm of the GFRP rods. 40mm of the embedded rod was prevented from bonding to the concrete by coating with temperature resistance grease or plastic tapes. The rebars were held by a retort stand at the centre of the 100mm cubic moulds, as concrete was cast inside the moulds to provide samples for the pull-out test, Figure 2.

During the pull-out test the composite rebar was gripped by the cross head of the 100 kN Schenck testing machine while the concrete cube was secured to the loading frame. Nuts and studding were used to prevent splitting of the concrete cube. The loading configuration is shown in Figure 3.

Pull-out tests were carried out on two sets of samples, one set treated in tap water (pH 7) and the other in alkaline solution (pH 12.5), for 30 days, 120 days or 240 days at room temperature, prior to testing. Pull - out tests were carried out under temperatures of 20-25, 40, 60, 80, 100 or 120°C. At each temperature range five samples were tested. A total of 180 samples were made and tested to evaluate the bond strength of the GFRP rebars to the concrete under various conditions. The standard diameter, maximum diameter and nominal cross section of the GFRP rebars were 12mm, 12.78mm, and 150.32 mm^2 respectively.

3.2. Tensile Test on composite rebars

Tensile tests were conducted on the composite rebar at range of temperatures according to the recommendation of JSCE 1992[4]. The bar length was 40 times the

diameter (ϕ) plus 100mm i.e. 580mm. Each end of the sample rebar was encased in a copper tube with a length of 70mm to prevent breakage at the jaw. This allowed the grips to hold the specimen without damaging the rod. The jaws were rounded and anchored the specimen securely such that no slippage occurred while the tensile force was applied. The anchoring section was 60mm for each end resulting in a gauge length of 460mm. The elongation of the bar was measured by a 25mm clip gauge attached at the centre of the bar. In addition, a strain gauge, length 2mm, was positioned at the centre of the rebar. Thus, strain was measured and verified simultaneously by the two methods of measurement. The tensile load was applied with a 10-Tonne Schenck testing machine equipped with a 250°C heating chamber.

The load was applied under displacement control at the rate of 1mm/min. The surface temperature of the specimen was measured with a thermocouple installed on the surface of the specimen, at its mid point. At each test temperature the elongation of the bars was recorded by two digital display monitors at each 1 kN increment of load increase, and the tensile elastic modulus at each temperature was calculated from the stress-strain relationship. The tensile tests were carried out after the surface temperature of the specimen reached a predetermined level (i.e. 25°C, 80°C and 120°C) and the specimen was allowed to stand for 12 minutes until temperatures the core of the rebar became equal to the surface temperature. This time period required for thermal equilibrium was established separately using a specimen with thermocouples mounted in a drilled hole at the centre of the rod. In the test the breaking loads and elongation to failure under tension were measured

3.3. Environmental Conditioning

Some samples used for the tensile tests were subjected to environmental exposure to an alkaline solution 1mol/litre of NaOH, pH=13. The procedure for such conditions involves total immersion of the specimen in a bath of the test liquid under controlled temperature conditions. The thermostatically controlled immersion bath was set at 60°C in order to accelerate the effects of alkaline conditioning. After immersion, specimens were tested in tension immediately in order to avoid any drying of the samples. In order to prevent infiltration of the solution via the ends of the test pieces during immersion, both ends were coated with epoxy resin. The G1 rods were kept for 30 days, 120 days or 240 days in alkaline solution at 60°C. The G2 and G3 rods were kept for either 30 days or 120 days. The subsequent tensile tests, were carried out at 20-25°C, 80°C and 120°C. As a control, untreated rods were tested at the same temperatures.

3.4. Microscopic Examination

After mechanical testing and environmental exposure selected samples were examined using scanning electron microscopy to identify any visible sign of deterioration in the material and to identify failure modes.

4. PULL - OUT TEST RESULTS

Results of the pull-out tests for each set of samples are given in Table 2.

Loads are measured by the electronic load cell of the tensile machine and slip between the rods and the concrete is measured by three DC voltages LVDT’s two at the loaded end and one at the free end, as shown in Figure 4.

While the free end LVDT's measured free end slip directly, the loaded-end measurement needed to be adjusted as the basic measurement includes elastic extension of the rod itself. The elastic extension of the rebar outside the concrete cube is subtracted from the measure loaded end slip using Equation 1.

Actual slip = measured slip – (Load x Length (=gauge length – unbonded length))/E.πr^2 (1)

Where πr^2 is the effective cross sectional area of the rod.

The average shear stress of the bond is then given by

$$u_{\max} = \frac{P_{\max}}{\pi 2 r l_b} \quad (2)$$

Where P is the bond force, 2r is the diameter, l_b is the bond length.

Figure 5 shows typical bond stress versus displacement curves at the free end and the loaded end. The bond strength calculated by equation 2 is maximum interfacial shear stress in the anchored region, and is calculated for comparison purposes only. It should be noted that the stress distribution due to the pull - out force from the rebar to the surrounding concrete is not uniform and the modulus of the rebar is different from that of the concrete. Consequently different rebar lengths or rebar diameter would result in different average values of bond strength. In this set of experiments the l/d ratio was kept constant.

Figure 6 shows the variation of bond strength due to temperature for those samples, which were treated in water in comparison to the samples treated in alkaline solution for 28 days, 120 days or 240 days.

4.1. *Discussion of the Pull - out TEST RESULTS*

Results of the pull - out test show that the bond strength is decreased as the test temperature is increased. Two types of failure were observed pull-out of the rod and concrete splitting along the rod. If splitting occurred the failure was a cohesive failure in the matrix and not a bond failure. For this reason the results presented in Figure 6 do not include splitting failures.

The effects of immersion period on the bond strength i.e. one month, four months and eight months, are also shown in this work. Tests at lower temperatures i.e. 20ºC, 40ºC and 60ºC showed an increase in the bond strength of more than 40% after eight months immersion compared to one month immersion for both sets. At higher temperatures, i.e. 80ºC, 100ºC and 120ºC, the bond strengths of the two sets of samples immersed for 240 days were 10-30% greater than for those samples immersed for one month.

The reduction in interfacial bond strength for all samples tested appears to depend primarily on the temperature of the pull - out test. If all the results are plotted together as nominal strength, relative to tests conducted at room temperature for a given exposure time, a single relationship can be determined as illustrated in Figure 7.
An equation $k_u = 1 - 0.000004T - 0.00003T^2$ provided a reasonably good fit to the expanded data where $k_u =$ ratio of strength at T (°C) over strength at room

temperature. This indicates that the relative importance of testing in an alkaline or water environment is small.

The de-bonded length of some tested samples was investigated using a scanning electron microscope. Some representative micrographs from this study are shown in Figure 8 and Figure 9. The matrix at the surface of the rebar appeared to have been abraded in all cases. These micrographs also indicate significant rupture of glass fibres over the de-bonded length for tests at 120ºC in contrast to samples tested at 40ºC where fibre breakage was very limited. No other significant difference in tests at 40°C and 120°C was seen apart from slightly greater fragmentation of resin at the higher test temperatures. In general terms the amount of damage observed at the de-bonded surfaces increased with the rise in the temperature at which pull - out failure occurred.

5. TENSILE TEST RESULTS

All tensile test specimens exhibited fibre rupture in the gauge length. This confirmed that the alignment of the rods and grip system used worked successfully. The tensile stress-strain curves for all test temperatures and all environmental exposures were linear to failure with failure being a sudden catastrophic rupture. The elastic modulus was measured by taking the gradient of the linear relationship between stress and strain. The strength was defined as the maximum load divided by the initial cross section of the rod.

The results for tensile test strength on G1 rods for different environmental treatments are shown in Figure 10. There is a general decrease in measured strength with both the temperature of tensile testing and the duration of exposure in alkali. The strength results for G2 and G3 rebar and modulus data for all rebars exhibit similar trends and all data is presented in Table 3. In all cases the scatter in the results was small with coefficients of variation generally less than 10%.

The reduction in strength and elastic modulus of the rebar is inevitably linked to the degradation in the properties of the glass fibres at the various conditions of testing. For this reason, the strength reduction for each rebar was plotted against test temperature normalised to the strength of the rebar measured at 20°C for each set of environmental exposure conditions. This revealed that the normalised data sets from each environmental condition were so similar that a single trend line could be drawn though the full set of data, Figures 11-13. This allows a single equation to be derived that predicts the relative strength reduction as a function of temperature, irrespective of the starting condition of the rebar.

i.e. :

$$\frac{\sigma_{fT}}{\sigma_{f\,20°C}} = k_{\sigma} \qquad (3)$$

where $\sigma_{f\,20°C}$ and σ_{fT} are the ultimate tensile strength of the rebars at 20°C and 20°C + ΔT°C respectively, and where the rebar at 20°C and 20°C +ΔT°C have the same environmental history.

According to the best fit obtained from fitting the data in figures 11-13 the values of k_σ for each rod are

G1 rod

$$k_\sigma = 1 - 0.0041\Delta T \qquad \text{for } 20 \le \Delta T \le 120 \ (\Delta T \text{ in } °C) \qquad (4)$$

G2 rod

$$k_\sigma = 1 - 0.0025\Delta T \qquad \text{for } 20 \le \Delta T \le 120 \qquad (5)$$

G3 rod

$$k_\sigma = 1 - 0.0034\Delta T \qquad \text{for } 20 \le \Delta T \le 120 \qquad (6)$$

The results obtained from this work compare well with those quoted by Blontrock et al.[5] with their equivalent expression for the reduction in glass strength, $k_\sigma = 1 - 0.0025T$ for $20 \le T \le 400$ matching our data for the G2 rod exactly.

By extrapolating the equations (4-6), a temperature can also be determined at which the rebars are predicted to have zero strength (to $k_\sigma = 0$), Table 3. This is only an indicative measure of rebar performance as matrix degradation would ensure that the rebar could not carry load well before these ultimate temperatures.

The value of reduced elastic modulus as a function of temperature can be expressed in a similar way, using the relationship:

$$\frac{E_{fT}}{E_{f\,20°C}} = k_E \qquad (7)$$

where $E_{f\,20°C}$ and E_{fT} are the modulus of the composite rebars at 20°C and 20°C +ΔT°C respectively.

The reduction in modulus follows a similar pattern to that of strength and for the G2 and G3 rebar it is also possible to produce an equation that covers all environmental treatments. However for the G1 rod, the change in modulus of the rebar with temperature after different environmental treatments is different and separate equations are required, Figures 14. The reason why the G1 bar exhibits such different behaviour is unclear, but it could be linked to the identify of its resin matrix. Orthophthalic resins as used in G1 rebar exhibit reduced chemical resistance to alkali compared to the vinyl esters used in G2 and G3 rebar. This may result in the initial modulus being degraded significantly as a result of matrix attack and subsequent thermal effects on the matrix are less significant. The difference between the behaviour of the G1 rods with respect to modulus and strength may reflect a minimal influence of resin properties on ultimate rebar strength.

The relevant expressions derived from Figures 14-16 are:

G1 rod

$k_E = 1 - 0.0054\Delta T$ (unexposed condition) for $20 \leq \Delta T \leq 120$ (ΔT in °C) (8)

$k_E = 1 - 0.0052\Delta T$ (A1 condition)

$k_E = 1 - 0.0031\Delta T$ (A2 condition)

$k_E = 1 - 0.0019\Delta T$ (A3 condition)

G2 rod

$k_E = 1 - 0.0017\Delta T$ for $20 \leq \Delta T \leq 120$ (9)

G3 rod

$k_E = 1- 0.0045\Delta T$ for $20 \leq \Delta T \leq 120$ (10)

7 DISCUSSION

The results generated in this programme clearly show that the properties of GFRP rebar deteriorate with temperature and time of exposure to alkaline environments. In contrast the strength of the GFRP rebar-concrete interface actually increases with time and appears relatively insensitive to exposure to alkaline environments, Figures 6 and 7.

The trends for bond strength may be explained by the gradual increase in concrete strength over this time period. The appearance of the rebars from bonded region after pull – out indicates the failure has involved abrasion-like fracture processes on the rebar surface. The stronger the cement layers at the interface, the better the mechanical bond that would create between the rough rebar surface and the concrete. The bond strength does however decrease in strength with temperature, as identified in the Eurocode standards. However it is generally assumed in the Eurocode that the reduction in concrete strength is linear with temperature unlike the bond strength reduction in this case. Moreover, a probable reduction in concrete strength of less than 10% is predicted by the Eurocode relationship at 120°C whereas the measured reduction in bond strength amount to approximately 40%. The additional strength loss must be due to additional factors such as a weakening of the surface layer of the rebar itself, probably due to resin softening, and possibly thermal effects such as differential thermal expansion between rebar and the concrete.

The reduction in the strength and stiffness with temperature of the rebars themselves is in most cases consistent for each type of rebar irrespective of the environmental history. These results for strength are similar to those published by Blontrok et, al.[3] who found a linear decrease in strength for glass fibre rebar as temperature increases from 20°C. Blontrok et, al. however reported that stiffness of his rebar did not decrease until a temperature of 100°C was reached – thereafter the decrease in modules was linear with temperature increase.

The reduction in strength with temperature is relatively easy to explain. It is unlikely that temperature effect is linked to any significant reduction in glass fibre strength within temperature range considered. It is probable that the strength reduction is instead due to changes in effective stress transfer occurring within the rebar. A composite rebar is considered to be largely unidirectional structures with the fibre fully impregnated by resin and good bonding between the fibre and matrix. When one fibre breaks locally it can continue to contribute to the strength of the overall composite, as the broken fibre will still carry some load at positions remote from the fracture. Multiple fractures of fibres will occur before final rupture of the bar. When the interface becomes degraded the stress transfer required to continue loading broken fibre is reduced and the strength of the composite is reduced accordingly. The extreme situation is when the fibres exist as a bundle of fibres with no resin. The strength of a loose bundle of fibres compared to average strength of individual fibres varies depending on the probability distribution of flaws in the fibres which is characterised by the Weibull shape factor. A good treatise on this subject is given by Chou[7]. For glass fibres the typical values of Weibull shape factor are about 10-11[7] and this would suggest a bundle to average fibre strength ratio of about 0.75. The strength of the

composite itself never completely reflects the average strength of the individual fibres but can rise as high as 0.95 in some cases. It is possible that the effect of temperature is to reduce the bonding efficiency and impair stress transfer within the composite such that the rebars progressively acts more like a bundle of loose fibres than a solid composite as the temperature rises. The effect of the alkali exposure could then be to reduce the baseline strength of glass fibres without affecting the stress transfer at each test temperature. This would explain why the normalised reduction in strength with temperature, is similar for each composite system tested after each aging condition, Figures 11-13.

However this may only the part of the explanation. It is apparent that the rebar is not exhibiting a high strength before exposure to either temperature or alkaline environments. A unidirectional glass fibre composite with aligned fibres might be expected to exhibit strength of the order of at least 900 MPa, possibly higher. The measured tensile strength for all three rebars is of the order of 400 MPa. The low measured strength could be due to misaligned fibres, but inspection of rebar after resin burn-off, Figure 18, shows that the fibre alignment is good. The more likely explanation is that the fibres have been damaged by the various operations involved in manufacture. A rough back-calculation based on a simple rule of mixtures approach would suggest that the mean fibre strength should be of the order of 400/0.6 MPa, i.e. 670 MPa which is much lower than virgin strength of glass fibres which can reach 2200 MPa. Damage to the fibres during processing would also result in an effective reduction in the Weibull shape factor and increase the strength reductions due to a breakdown in the interfacial stress transfer mechanisms and this would explain the strength reductions observed of the order of 40%.

The measured rebar modulus is also a bit low in all cases. A volume fraction of 0.6 with well-aligned fibres would be expected to yield a modulus of about 43 GPa, whereas the measured values start about 39 GPa. This is not particularly low and could well be explained by slight imperfections in orientation and damage to the glass fibres. It is however more difficult to explain why the modulus decreases in the temperature range examined. The glass fibres will not soften to any significant degree over this range and the resin makes an insignificant contribution to the overall modulus. The only feasible explanation is again the stress transfer between the fibre and matrix breaks down as the temperature increase, thereby reducing the overall stiffness of the composite. The changes in the rate of decrease in modulus with temperature exhibited by each rebar system can then be attributed to transition in the resin. The vinyl ester in rebar G2 looks to be stable over the full range of temperature tested, whereas the vinyl ester of rebar G3 undergoes a transition at some temperature after 80°C many vinyl ester posses glass transition temperatures in the region of 100°C. The resin in rebar G1 is an isophthalic polyester, which has a much lower temperature resistance (lower Tg). The polyester resin system is also much more susceptible to chemical attack by alkalis which in turn means that the baseline room temperature modulus is reduced dramatically. It is interesting to note that the subsequent rate of decrease in modulus as a function of temperature is lower for the polyester rebars that have been exposed to alkali. This suggests the composite is almost fully degraded and the stress transfer is at a minimum even at room temperature and increasing the temperature cannot significantly further degrade the composite.

8 CONCLUSIONS

The results presented in this programme allow us to make a number of conclusions:

The glass fibre-concrete interface is degraded by an increase in temperature within the range 20 - 120°C.

The reduction in interfacial bond strength is similar for samples that are exposed to alkali or neutral environments.

The interfacial bond strength increases with time at room temperature.

The normalised degradation in bond strength with an increase in temperature obeys a similar relationship irrespective of the prior conditioning of the samples.

The glass fibre strength and modulus is reduced by exposure to alkali and by testing at elevated temperatures.

The nature of the resin matrix determine the magnitude and rate of degradation of the rebar.

There is strong evidence to suggest that the magnitude of the degradation in strength and stiffness in the rebar after environmental exposure and at elevated temperatures is linked to change in the stress transfer efficiency between fibres and matrix within the composite.

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Table 1 Characteristics of the GFRP rebars used in this work, manufacturers data

GFRP rod	Diameter (mm)	Shape	Tensile strength (MPa)	Elastic modulus (MPa)
G1	12.7	Round	655	40800
G2	12.7	Round	655	40800
G3	12.7	Round	800	42000

Table 2 Pull - out test results at differing temperatures after immersion in water and alkaline solutions

Environment for immersion prior to testing at 20-25°C	T (°C) during pull – out test	Average bond strength (MPa) after 30 days immersion in environment	Average bond strength (MPa) after 120 days immersion in environment	Average bond strength (MPa) after 240 days immersion in environment
Water	20- 40 60 80 100 120	9.90 (2.5) 9.71 (1.3) 9.11 (2.0) 9.02 (1.9) 6.39 (1.2) 6.13 (1.5)	14.36 (1.2) 12.09 (1.3) 11.27 (1.4) 9.70 (1.5) 8.83 (1.1) 6.76 (1.2)	16.37 (2.0) 15.57 (1.4) 14.11 (1.1) 13.33 (0.4) 11.67 (2.0) 8.73 (2.0)
Alkaline solution NaOH, pH 12.5	20 40 60 80 100 120	10.14 (1.5) 9.17 (2.1) 9.33 (2.3) 9.13 (1.9) 4.83 (2.0) 5.02 (1.5)	13.65 (2.0) 12.27 (1.8) 11.65 (2.1) 10.11 (1.9) 9.04 (0.9) 6.56 (0.7)	15.07 (1.9) 14.17 (2.0) 14.11 (1.3) 12.93 (2.0) 10.33 (1.6) 7.34 (1.2)

*values in brackets are standard deviations

Table 3 Prediction of the temperature at which there is no strength in the rebars

Rebar type	Temperature at no strength (ºC)
G1	264
G2	420
G3	314

Table 4 Properties of the GFRP rebars at the various environments

Rebar types	Testing temperature (ºC)	Environmental Condition	Bond strength (MPa)	Tensile strength (MPa)	Elastic modulus (GPa)
G1	20-25	Unexposed	9.90*	366 (0.05)	39 (0.03)
G1	80	Unexposed	9.02*	277 (0.09)	27 (0.05)
G1	120	Unexposed	6.13*	223 (0.05)	18 (0.05)
G1	20-25	A1	10.14+	346 (0.05)	36 (0.02)
G1	80	A1	9.13+	252 (0.05)	20 (0.02)
G1	120	A1	5.02+	193 (0.08)	18 (0.06)
G1	20-25	A2	13.65+	326 (0.05)	27 (0.03)
G1	80	A2	10.11+	242 (0.05)	19 (0.13)
G1	120	A2	6.56+	186 (0.09)	19 (0.03)
G1	20-25	A3	15.07+	286 (0.07)	22 (0.05)
G1	80	A3	12.93+	236 (0.07)	18 (0.05)
G1	120	A3	7.34+	174 (0.07)	18 (0.05)
G2	20-25	Unexposed	-	416 (0.05)	37 (0.05)
G2	80	Unexposed	-	362 (0.05)	33 (0.05)
G2	120	Unexposed	-	332 (0.05)	31 (0.05)
G2	20-25	A1	-	349 (0.07)	31 (0.05)
G2	80	A1	-	289 (0.09)	28 (0.05)
G2	120	A1	-	268 (0.09)	26 (0.07)
G2	20-25	A2	-	333 (0.09)	29 (0.09)
G2	80	A2	-	280 (0.11)	26 (0.08)
G2	120	A2	-	223 (0.05)	24 (0.15)
G3	20-25	Unexposed	-	396 (0.03)	41 (0.08)
G3	80	Unexposed	-	330 (0.07)	35 (0.05)
G3	120	Unexposed	-	246 (0.11)	22 (0.09)
G3	20-25	A1	-	375 (0.09)	39 (0.05)
G3	80	A1	-	295 (0.07)	32 (0.05)
G3	120	A1	-	240 (0.08)	21 (0.05)
G3	20-25	A2	-	299 (0.05)	33 (0.05)
G3	80	A2	-	260 (0.05)	31 (0.12)
G3	120	A2	-	210 (0.09)	17 (0.10)

- bond strength of the specimen exposed in water for 30 days

\+ Bond strength of the specimens which were immersed in alkaline solution at normal temperature for A1 (30days), A2 (120 days) and A3 (240 days) prior to testing.

Values in bracket are coefficient of variation for each set of test

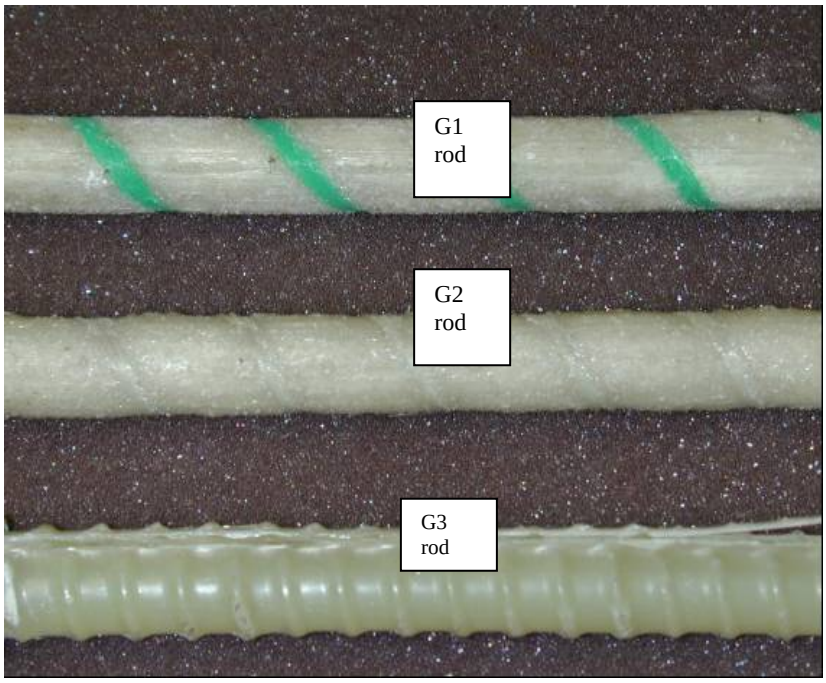


Fig 1 Types of the GFRP rebars used in this work

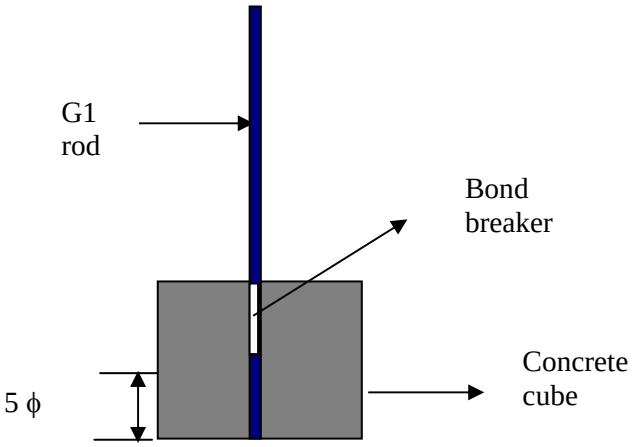


Fig 2. Pull - out test sample

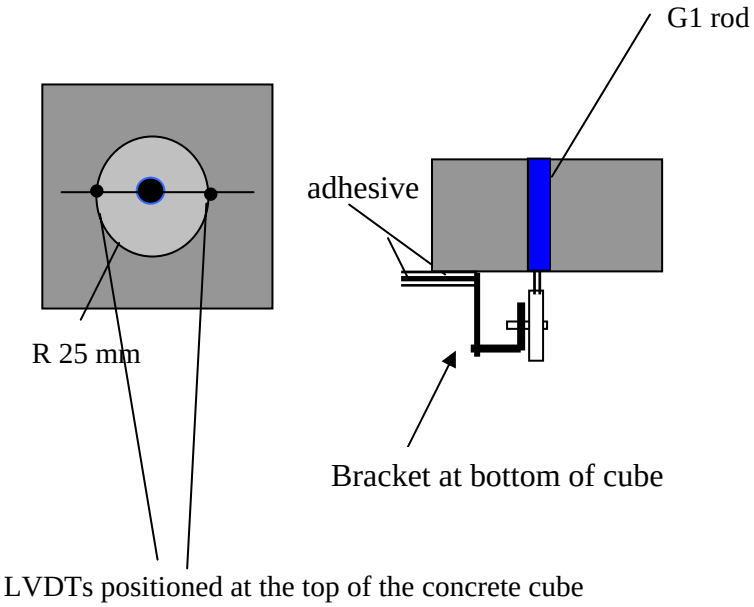
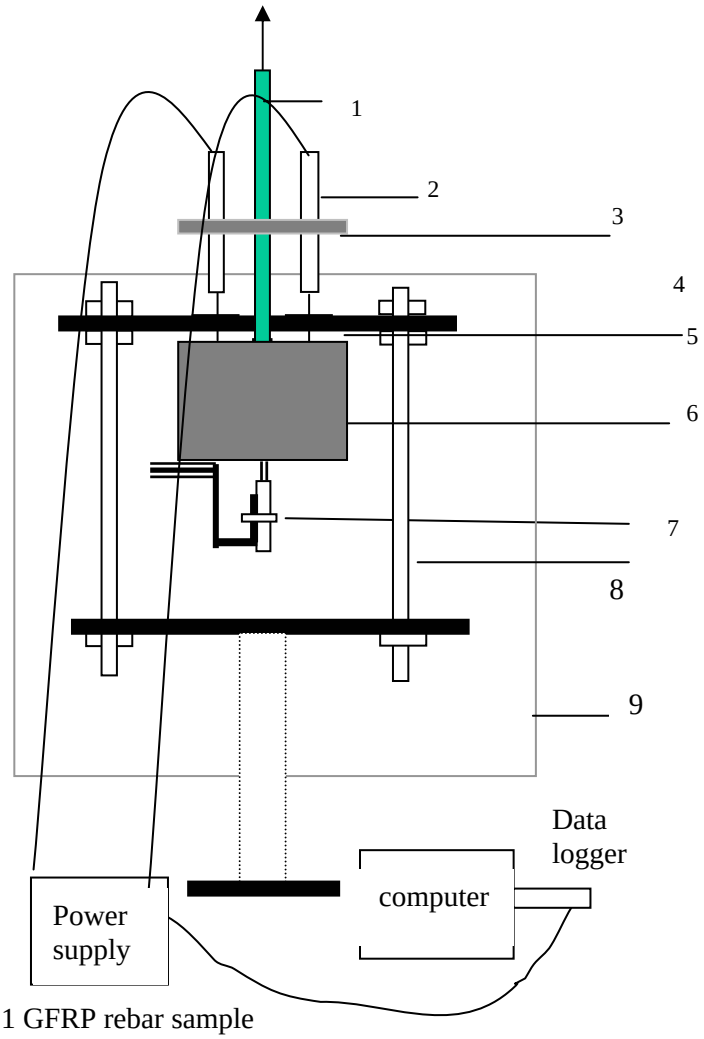


Fig 3. Relative movement points of the GFRP rebars in the pullout test



1 GFRP rebar sample
2 Top LVDT's
3 Mounting LVDT's to the rebar
4 Loading plate
5 PTFE
6 100mm concrete cube
7 Bottom LVDT
8 Testing frame
9 Heating chamber

Fig 4. Pull - out test geometry for elevated temperature testing

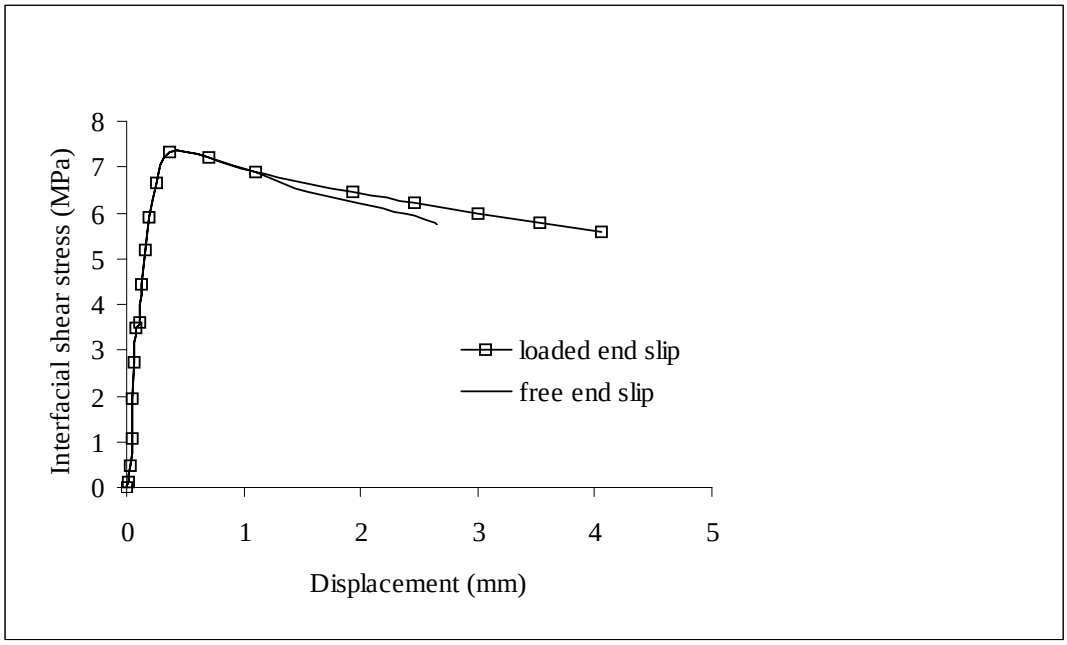


Fig 5. Typical interfacial shear stress via displacement of the rebar (relative movement) for a GFRP sample (G1 type), which has been immersed in alkaline for 240 days and tested at 120°C.

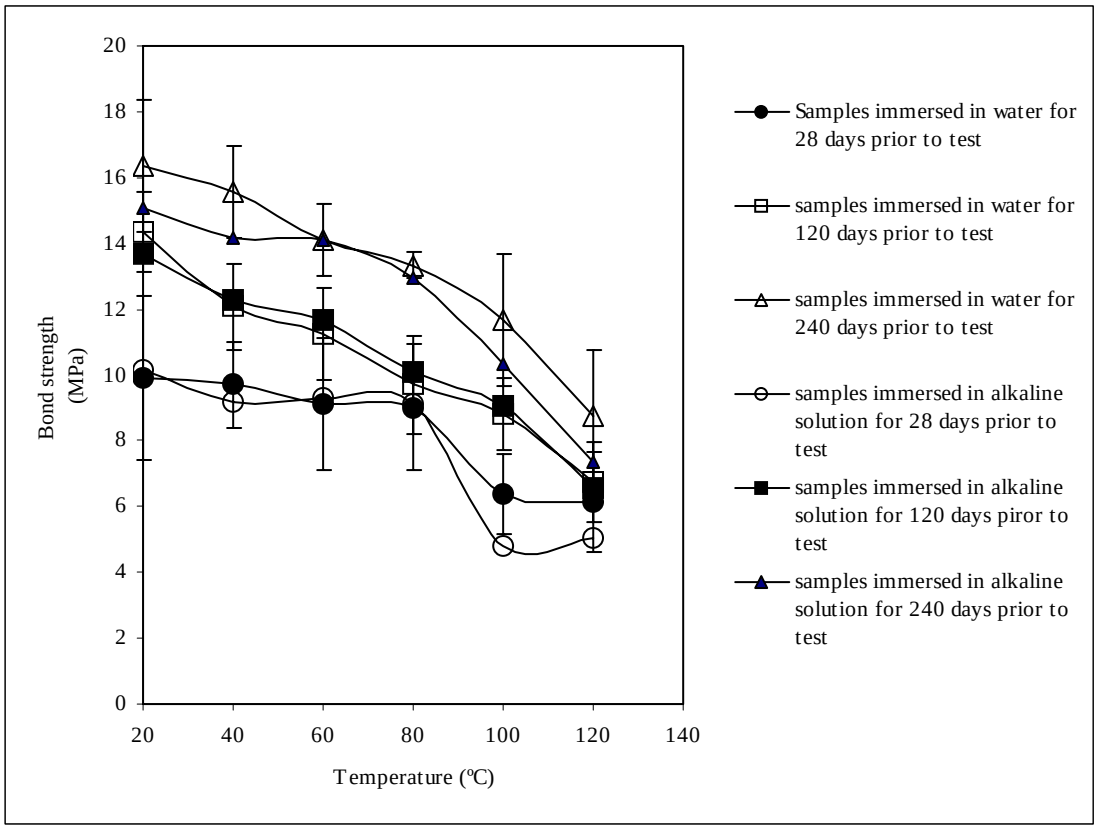


Fig 6. Comparison of pull - out test results for the composite rebar-concrete samples at differing temperatures and after various conditioning environments.
The standard deviations shown are, for clarity, only for those samples exposed to water.

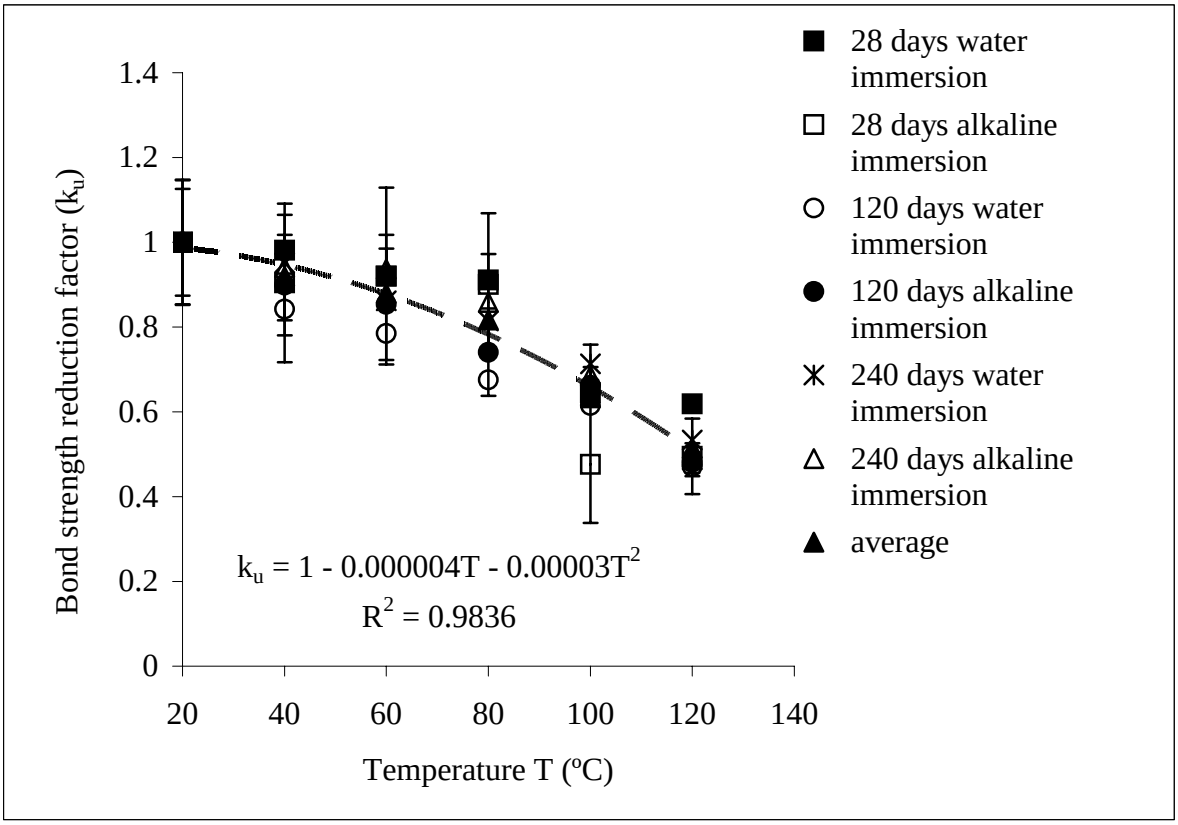


Fig 7 The relationship between the bond strength reduction factor and temperature. The reduction factor is calculated for each environmental conditioning regime and is based on the strength of the bond at a given temperature, relative to the strength at room temperature after that specific environmental treatment.

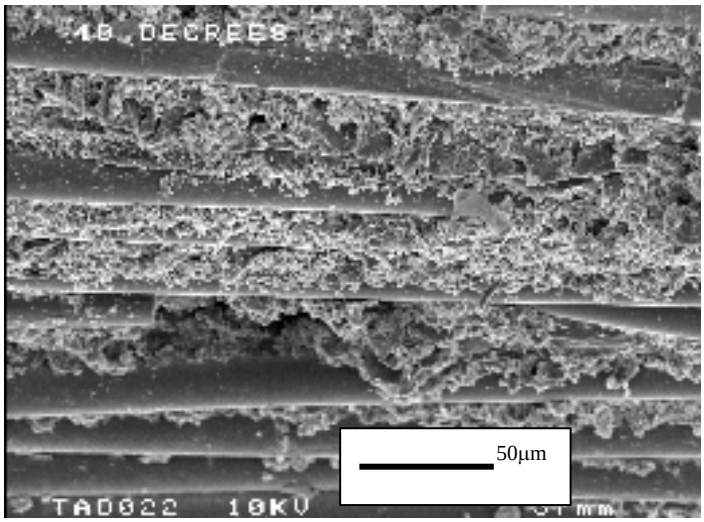


Fig 8 Abraded polymeric layer at the de-bonded surface of the rebar after pull - out at 40 °C

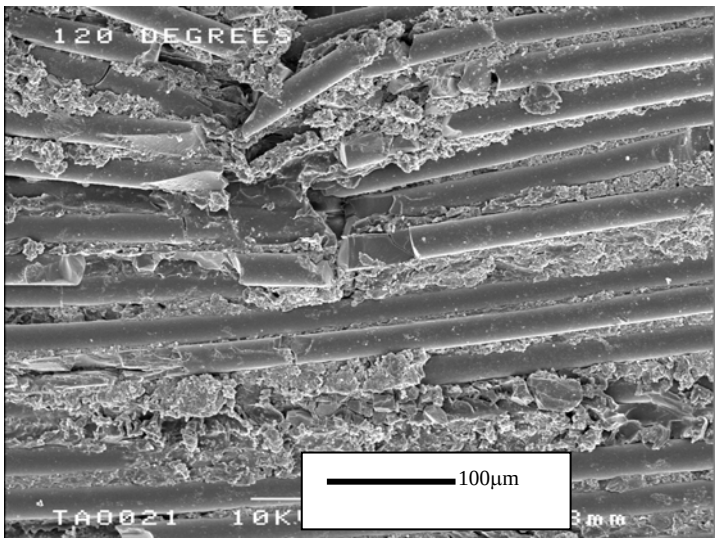


Fig 9 Surface of rebar shows failure of glass fibres along the de-bonded length of the composite rebar bar after pull - out test at 120°C

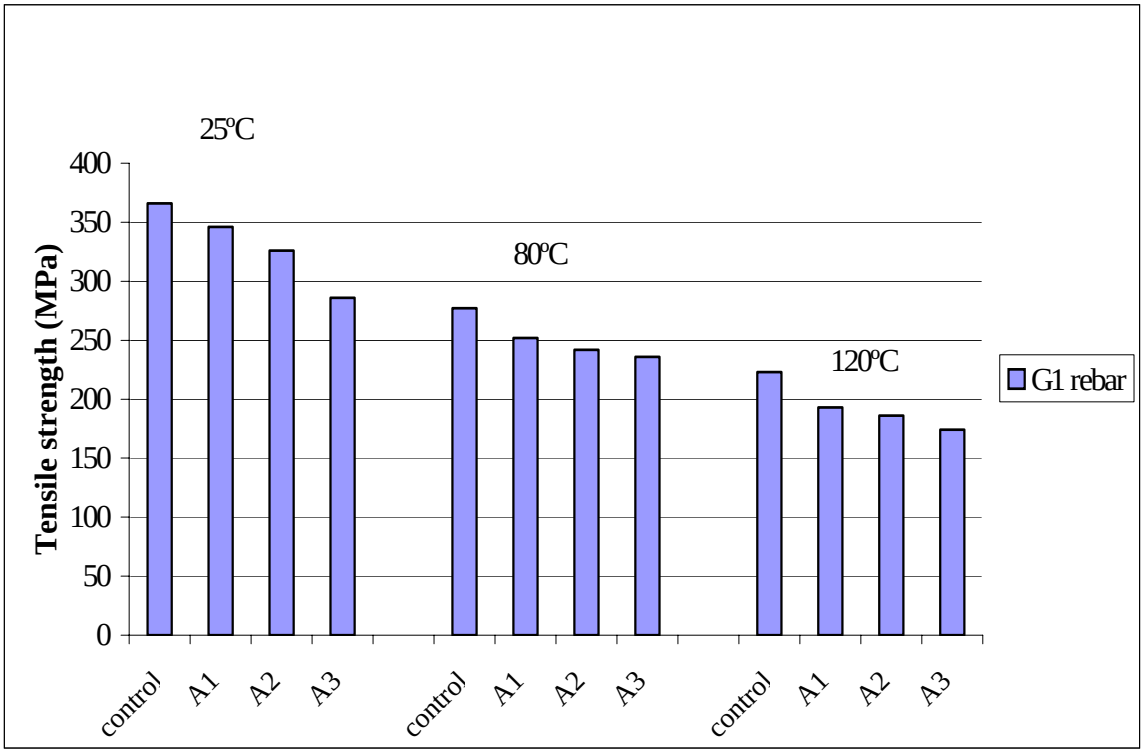


Fig 10. change in strength of G1 rod with different environment
A1 = 30 days at 60°C in alkaline solution
A2 = 120 days at 60°C in alkaline solution
A3 = 240 days at 60°C in alkaline solution

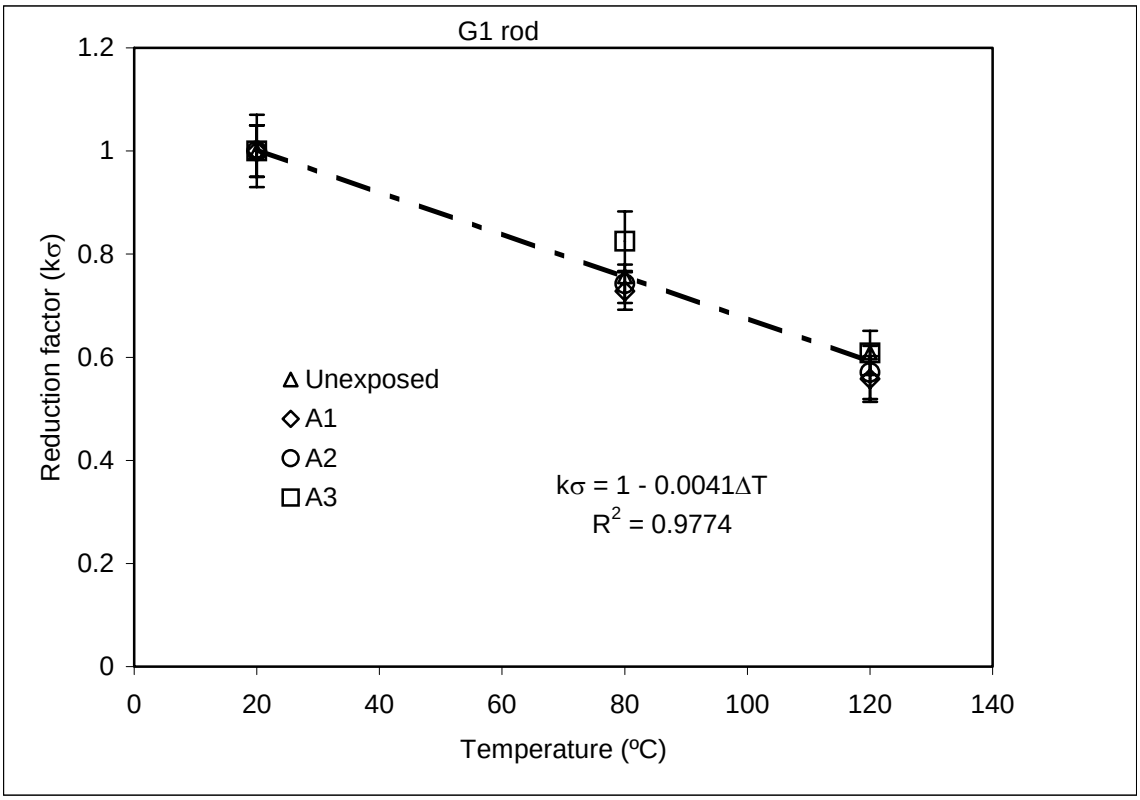


Fig 11 Temperature dependent tensile strength of G1 rod

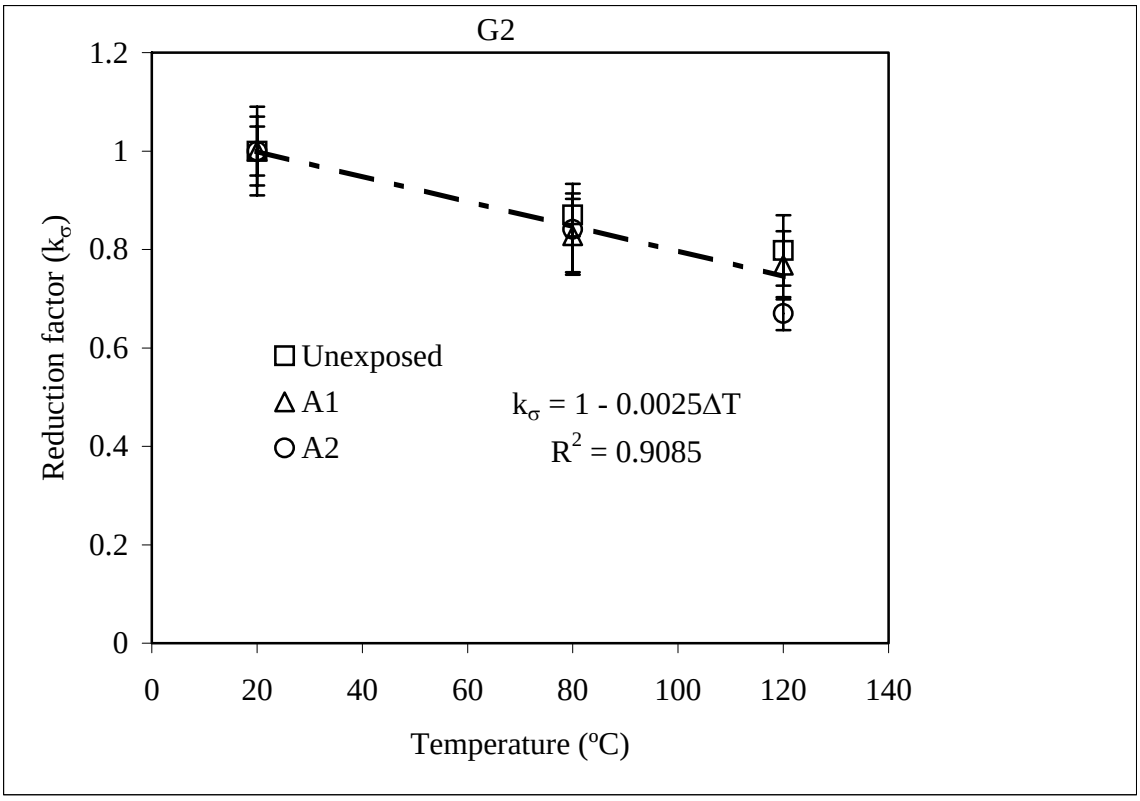


Fig 12 Temperature dependent tensile strength of G2 rod

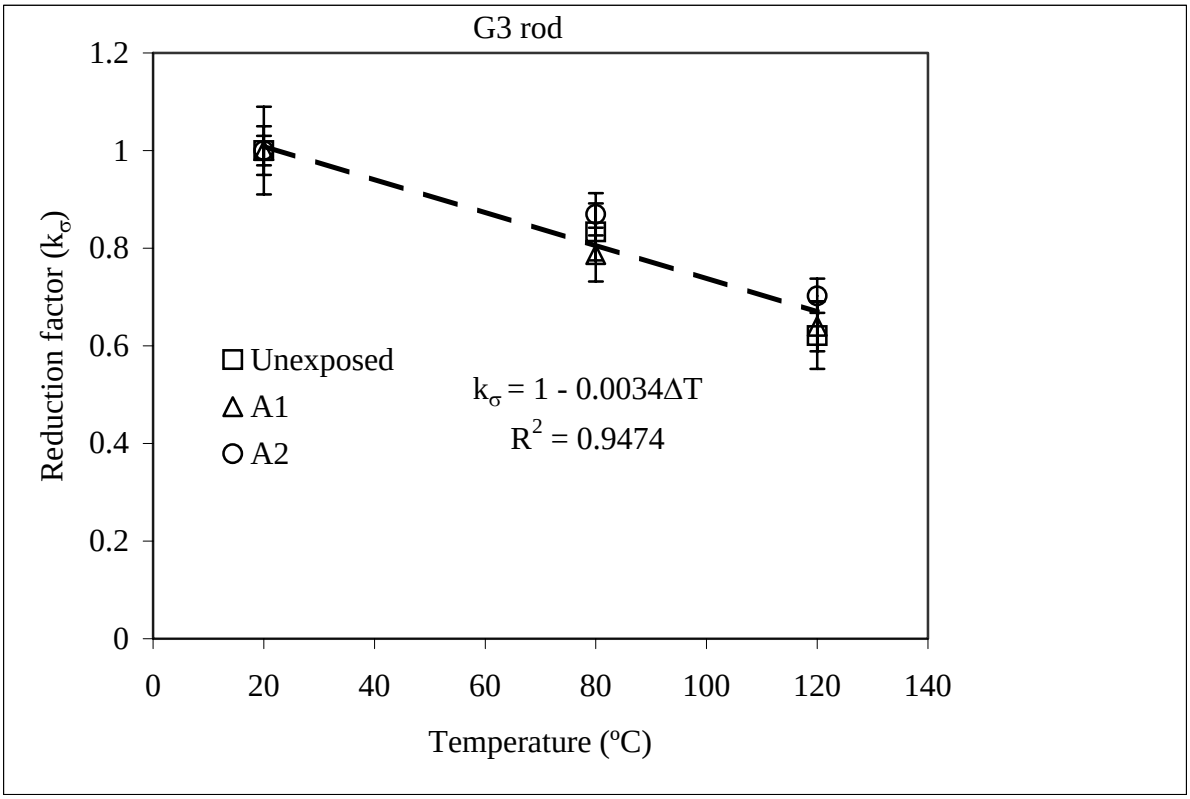


Fig 13 Temperature dependent tensile strength of G3 rod

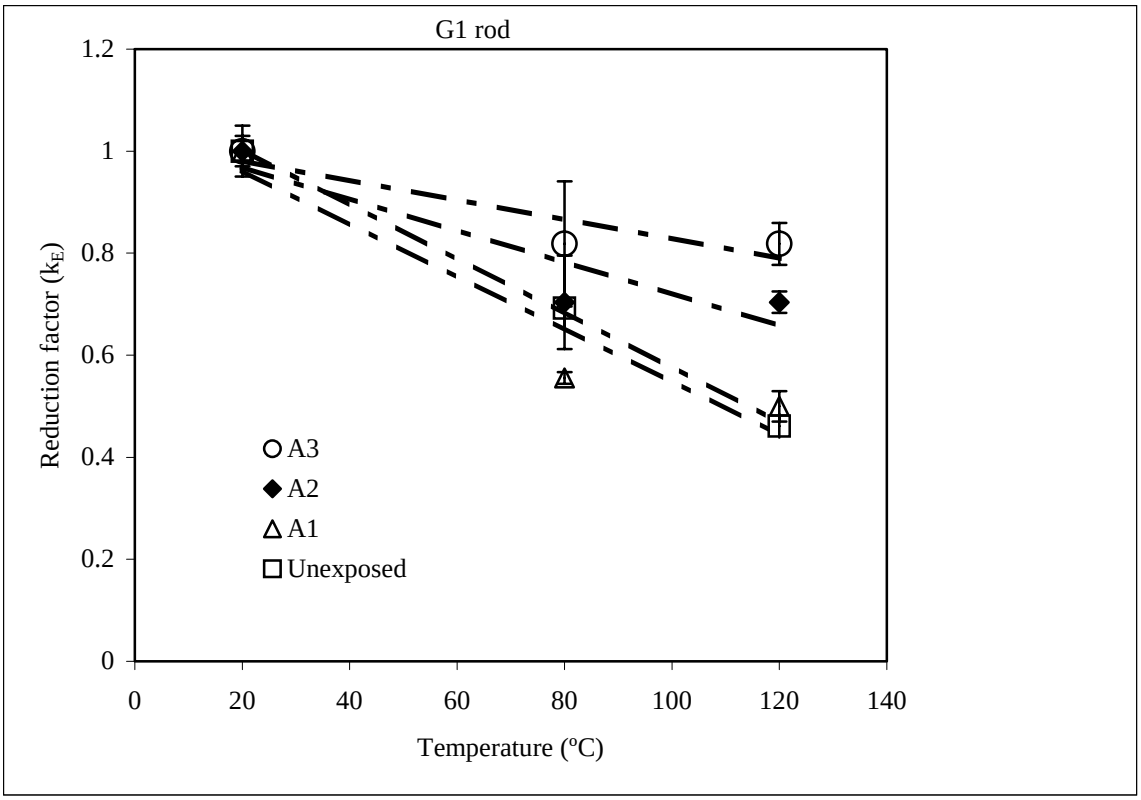


Fig 14 Temperature dependent elastic modulus of G1 rod at different conditions

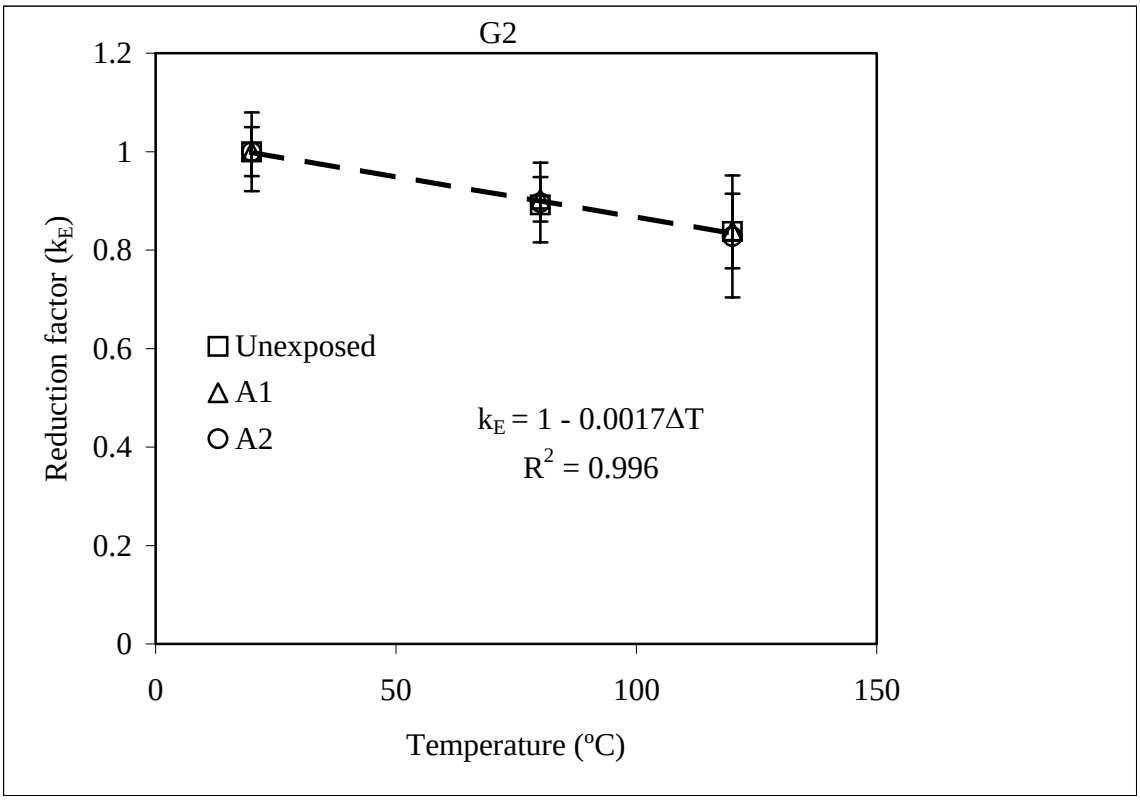


Fig 15 Temperature dependent elastic modulus of G2 rod

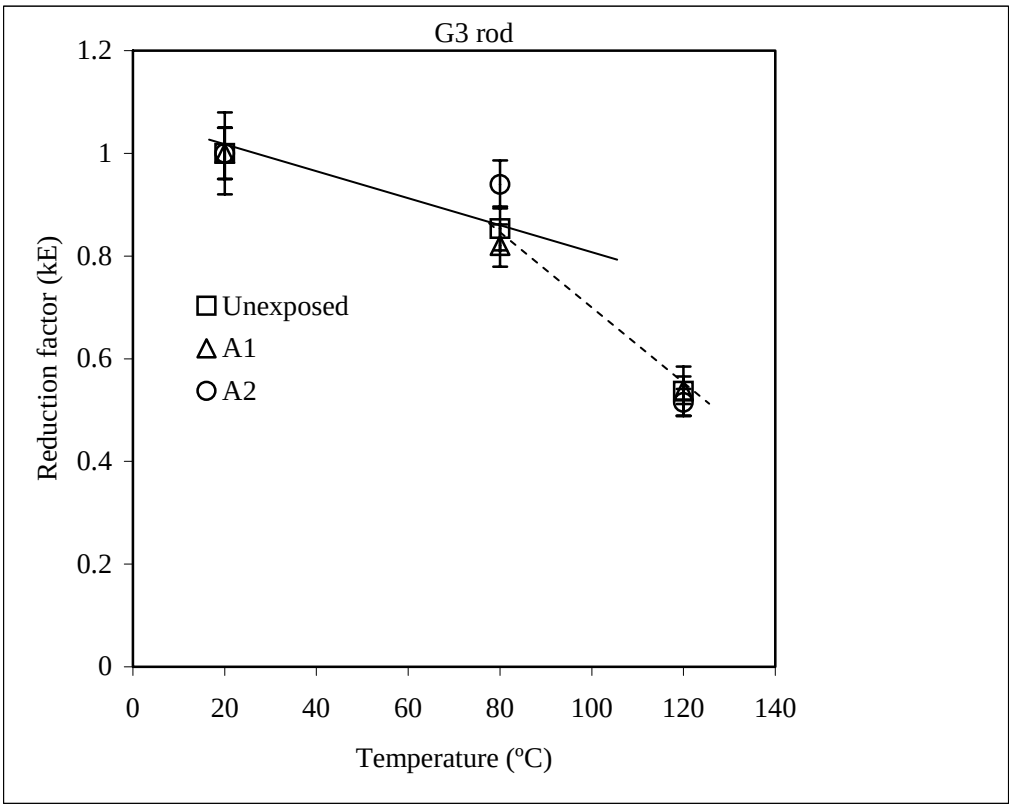


Fig 16 Temperature dependent elastic modulus of G3 rod

Fig 17 The middle of a G2 rod after resin burn-off showing revealing straight glass fibres.