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RESIDUAL STRENGTH OF CHOPPED STRAND MAT GLASS FIBRE/EPOXY COMPOSITE STRUCTURES: EFFECT OF TEMPERATURE AND WATER ABSORPTION

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ABSTRACT

The residual strength of chopped strand mat glass fibre/epoxy composites following exposure to different hygrothermal conditions was investigated. All residual tests were carried out according to ASTM D 3479 and D 3039 on tension-tension fatigue with a frequency of 5 Hz, a stress ratio of R= 0.5and maximum stress σ_{max} = 60 MPa. The residual strength curves were used to investigate the strength of chopped strand mat glass fibre/epoxy under the effect of temperature and the interactive environment of water absorption and temperature. The results showed that the chopped strand mat glass fibre/epoxy had high resistance toward tension-tension fatigue loading. However, the degradation of the tensile residual strength of chopped strand mat glass fibre/epoxy was significant with high water absorption at an elevated temperature.

Keywords: glass fibre; temperature; water absorption; residual strength.

INTRODUCTION

The mechanical properties may be considered the most important of all the physical and chemical properties of polymer matrix composites (PMC) for most applications, such as transportation, sports equipment, off-shore uses and infrastructure. Potential advantages expounded by proponents of PMC include a lower weight-to-volume ratio, high specific strength, high specific stiffness, good fatigue performance, versatile fabrication and lower maintenance costs. PMC made from chopped strand mat fibre have found potential in low-end applications. Chopped strand mat polymer composites are materials in which the reinforcing fibres are uniformly distributed. Uniform density ensures consistent fibreglass content and uniform properties in every direction. The typical end-use applications include various types of panels, bath equipment, cooling towers, as well as boat and automotive parts.

PMC, as chemically fabricated materials, are susceptible to damage such as resin cracking, fibre breakage and delamination. Kumar and Gupta (1998) reported that these types of failure, in turn, can be affected by chemical or physical changes to the polymeric matrix resin, loss of adhesion or debonding at the fibre/matrix interface, and a reduction in fibre strength and modulus with long-term use. Mechanical properties and the durability of composite materials are highly influenced by various environmental agents, such as elevated temperature, humidity, oxidation and UV radiation (Springer 1984; Mohlin 1988; Griffis et. al. 1988; D'Amore et. al. 1998; DeIasi and Whiteside 1978; Wang et. al. 2007; Bowles 1998; Leterrier et al., 1998).

Mechanical fatigue is the most common type of failure in structures in service. While some PMC components maybe subjected only to static load in their lifetime, most will be subjected to loads and stresses that vary with time. Materials behave very differently in response to loads that come and go (fatigue loads) than they do to static loads. These failures typically occur at stress levels significantly lower than the yield strength of the materials. Researchers have also described failure under long-term static load, i.e. static fatigue. Since the strength of the material deteriorates after each cycle, it is critical to know the residual strength after a life fraction of a component, so that its capacity for carrying cyclic and extreme static loads can be ensured (Philippidis and Passipoularidis, 2007). The relative importance of fatigue has yet to be studied where static conditions prevail.

Sullivan (1990) stated that a polymer is generally not in a state of thermodynamic equilibrium below its glass transition temperature (T_g). Aging at an elevated temperature degrades the tensile and fatigue strength of PMC. Experimental evidence has shown that high temperature (~200°C) causes a reduction in the bond strength of between 80 and 90%, as reported by Katz et al. (1999). Additionally, it is possible that the effect of temperature reduces the bonding efficiency and impairs stress transfer within the composite such that the rebar progressively acts more like a bundle of loose fibres than a solid composite as the temperature rises (Abbasi and Hogg, 2005). Blontrok et al. (1998) found a linear decrease in strength for glass fibre rebar with increased temperature (over20°C).

Temperatures above 30°C will cause an increase in the moisture uptake tendency of PMC in the long run and thus a reduction in the tensile and flexural strength of the fibres (Gopalan et al. 1989). Liquid uptake, which always involves water, is thought to be explained by Fick's Law (Hancox, 1998). The diffusion process is said to be driven by a concentration gradient. Moisture penetration into composite materials is partly conducted by diffusion, which involves the transport of water molecules into the matrix and, in some cases, into the fibres (Bao and Yee, 2002; Srivastava, 1999; Marom 1986). Water can diffuse rapidly into the micro-gaps between polymer chains. The second mechanism involves capillary transport into the gaps and flaws at the interface between the fibre and the matrix. This capillary flow, also known as water wicking, conveys water to the interior of composites. It tends to occur preferentially along the interface, if wetting of the fibres by the matrix is incomplete (Varelidis et al. 2000). Percolating flow and storage of water in micro-cracks possibly present in the matrix (particularly in the case of natural fibre composites) constitutes a third mechanism of moisture penetration into composites. Finally, the corrosion of glass fibres, the dissolution of soluble compounds in matrices, increased inter-laminar stresses and a reduction in strength and modulus are moisture-related events that affect the durability and damage tolerance of composite materials (Browning and Hartness, 1994). Exposure to a humid environment causes permanent damage to the material system. Hayes et al. (1998) concluded that the reduction in strength is not recovered when the material is desorbed, suggesting that exposure to moisture causes permanent damage in the material system. Water absorption can be detrimental to the fatigue strength of composites (Vauthier et al., 1998)

When designing PMC, consideration should be taken regarding changes in the environmental conditions, and if the material's properties will change due to changes in the temperature and water content; these aspects should be taken into consideration along with any external loads acting on the PMC. The combination of stress and a corrosive environment has a synergistic effect. However, there is very little information

available in the literature on the fatigue and tensile strength of PMC in response to environmental changes, especially chopped strand mat glass fibre materials.

The present study attempted to relate any environmentally-induced changes to the residual strength of chopped strand mat glass fibre materials and provides a well-rounded set of experimental data on the enviro-mechanical durability of a chopped strand mat glass fibre/epoxy system that is not currently found in the literature. The results from this work include the residual strength of chopped strand mat glass fibre/epoxy at different temperatures, the percentage (%) of water absorption by the chopped strand mat glass fibre/epoxy and the residual strength of the chopped strand mat glass fibre/epoxy with variable water content and temperature exposure.

EXPERIMENTAL WORK

Preparation of Test Samples

Chopped strand mat glass fibre/epoxy specimens were fabricated by the hand lay-up process according to Dyer and Isaac (1998). This method is perhaps the simplest, oldest and least complicated. This is a manual approach in which layers of fabric and resin are successively applied onto a mould. The mould surface was treated with release wax, and then with epoxy resin. The chopped strand mat glass fibres were laid over the epoxy resin. Each layer was saturated with epoxy resin that was specifically formulated to cure overnight at room temperature. After each layer of fabric was placed, a roller was used on the composite so that a strong bond was made between the layers of composite and the excess resin was squeezed out. The stacking of four layers chopped strand mat glass fibre was repeated. This laminate was allowed to cure at room temperature. Later, the glass fibre/epoxy composite laminate was machined into the desired dimension as recommended in ASTM D 3039, with a length of 150 mm and a width of25.0 mm. Figure 1 shows a chopped strand mat glass fibre/epoxy test sample before the static tensile and residual strength tests.

Figure 1. Chopped strand mat glass fibre/epoxy specimen before conditioning

Hygrothermal Exposure and Residual Strength Assessment

The specific hygrothermal exposures of the specimens are shown in Figure 2. For testing exposure to high temperature and water simultaneously, the specimens were pre-

dried in an oven at 80°C until no measurable weight change was observed. The pre-dried specimens were immersed in distilled water at room temperature and at 90°C. Specimens were removed from the solution and weighed to determine the amount of water that was absorbed. The net weight gain (M_g) was taken as the water content of the specimen. The weight changes are evaluated using the following expression (Hamada et al., 1995):

Net weight gain, M_g

$$M_g = (W_w - W_o) / W_o \quad (1)$$

where W_o is the weight of the dry specimen before immersion and W_w is the weight of the wet specimen after immersion.

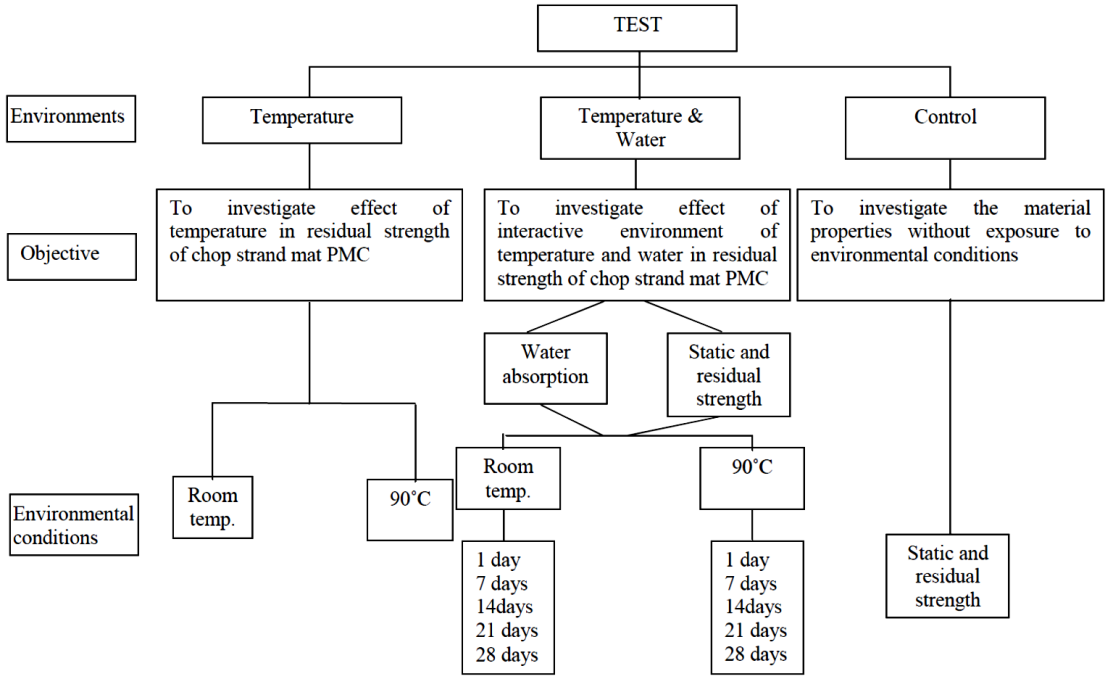


Figure 2. Flowchart on the overall experiment parameters

The experimental evaluation of the residual strength of the composite laminate was performed by exposing samples first to tension-tension fatigue (at an R-value of 0.5, maximum stress σ_{max} = 60 MPa and frequency of 5 Hz) up to a certain number of cycles n, and then to tensile static test (the crosshead speed was set to 0.4mm/min) until failure. An Instron 8801 testing machine was employed for performing the tension-tension fatigue and residual strength tests, as shown in Figure 3. The stress at which the laminate failed during the tension experiment was characterised as the residual strength of the laminate at *n* cycles. Three specimens were used for each test.

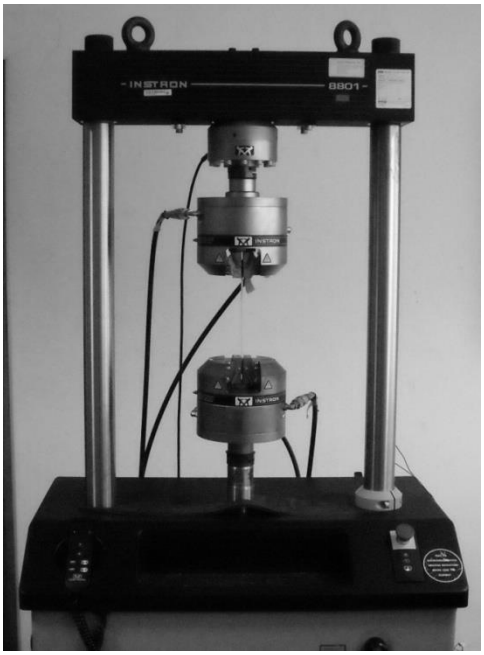


Figure 3. Tensile and residual testing on the test specimen

RESULTS AND DISCUSSION

The definition of failure for polymer composites under fatigue load is more complex than that of metallic materials as it involves many types of damage, such as matrix cracking, debonding, delamination, fibre breakage, etc. In this study, failure was defined as the inability of the specimen to bear the applied load, resulting in separation of the sample between the machine grips.

Effect of Temperature

The residual strength of the chopped strand mat glass fibre/epoxy at specified fatigue loading cycles and temperatures was measured; the results are shown in Figure4 and Figure5. These results indicate that the glass fibre/epoxy composite followed an almost linear reduction in its residual strength with fatigue cycles. It can be seen that replicate test on the specimens with the same environmental exposure produced similar results. Since the test standard deviation was small, there is relatively little variability in the data. These results indicate high consistency of glass fibre/epoxy mechanical properties and good resistance to cycling loading.

The effect of temperature on the residual strength of glass fibre/epoxy is shown in Figure 6. The diagram shows that temperature affected the residual strength, but not its fatigue behaviour, and the decrease in residual strength as a function of the number of cycles was small. It is unlikely that the temperature effects are related to any significant reduction in glass fibre strength within the temperature range considered in these experiments since the glass fibre will not soften to any significant degree within this range (Abbasi and Hogg, 2005). The higher degradation of strength of the glass fibre/epoxy likely arose from a decrease in the modulus of the resin binder in the composite specimens under increasing temperature. This behaviour can be partly attributed to decomposition of the resin.

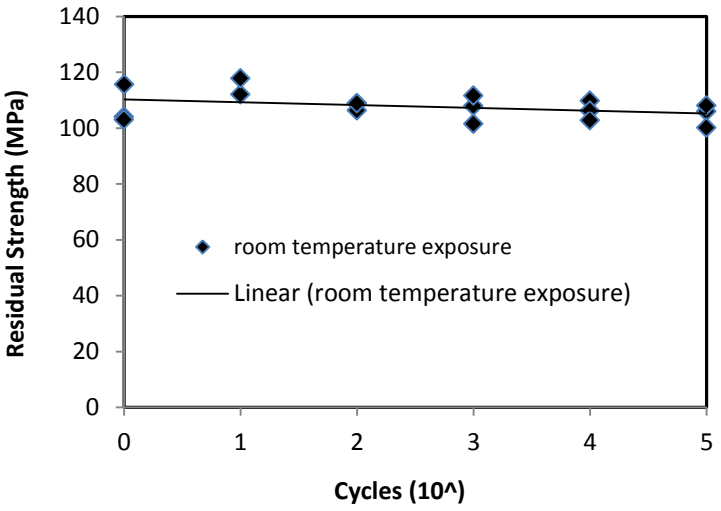


Figure 4. Residual strength curves of chopped strand mat glass fibre/epoxy exposed to room temperature

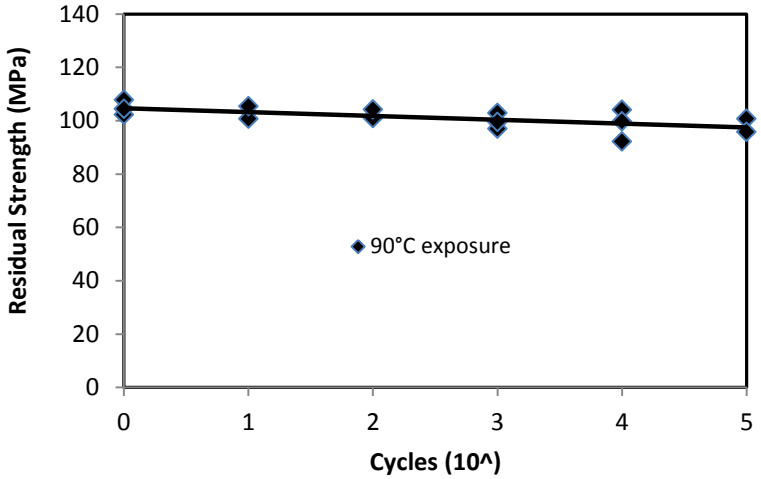


Figure 5. Residual strength curves of chopped strand mat glassfibre/epoxy exposed to 90°C

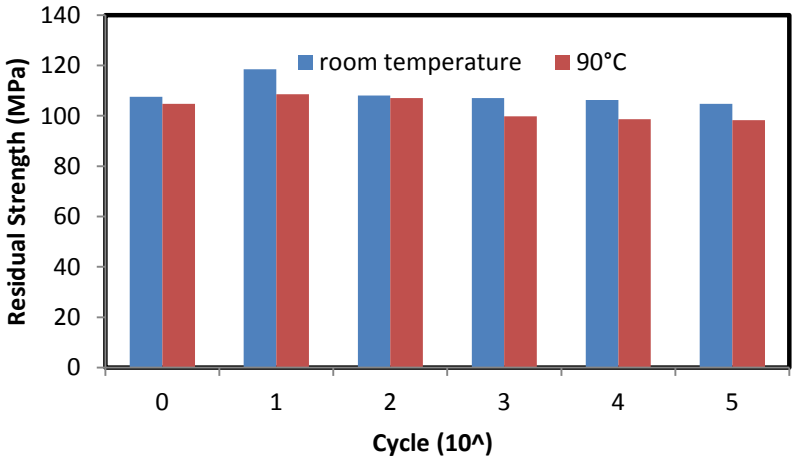


Figure 6. Comparison between the residual strength curves for chopped strand mat glass fibre/epoxy tested at different temperatures

Water Absorption

The results of the water ingress measurements are presented in Figure 7 and Table 1. The plot shows a steady increase in the amount of water absorbed. The water intake process for all the specimens was linear at the beginning, then slowed and approached saturation after a prolonged time. This indicates the time dependency of water absorption in these samples. The saturation time for glass fibre/epoxy has been estimated to be 30 days based on the research of Khalid et al.(2004). Exposure to high temperature along with water immersion (90˚C immersion temperature) made the specimens have a higher absorption rate and percentage water weight gain, which was about 4.5 times higher compared to the specimens immersed in room temperature water. The specimens showed a 4.09% water weight gain after immersion in distilled water at a constant temperature of 90˚C.The effect of temperature on water absorption can be clearly seen. On the other hand, it is worth noting that the overall net weight gain of the chopped strand specimens was less than for woven fabric specimens (Kueh et al., 2009). The data indicate consistently less water uptake for chopped strand specimens, due to the fact that the concentration is a function of the orientation of the fibres (Boukhoulda et al., 2006).

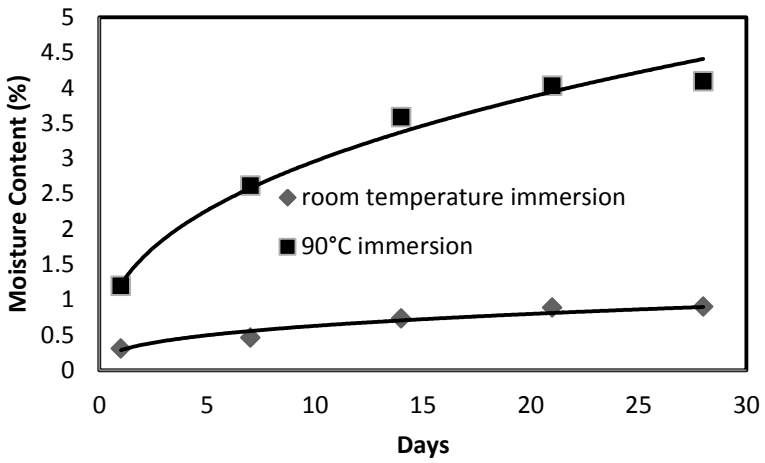


Figure 7.Water uptake of chopped strand mat glass fibre/epoxy immersed at different temperatures

Table 1.Water absorption of chopped strand mat glass fibre/epoxy after immersion at different temperatures

Conditions (immersion temperature/Days)	Net weight gain, M_q(%)		
	Specimen 1	Specimen 2	Specimen 3
Room temperature/1 days	0.269	0.292	0.355
Room temperature/7 days	0.425	0.426	0.525
Room temperature/14 days	0.698	0.681	0.825
Room temperature/21 days	0.818	0.885	0.962
Room temperature/28 days	0.804	0.982	0.917
90˚C/1 day	1.078	1.283	1.219
90˚C/7 day	2.758	2.414	2.674
90˚C/14 day	3.693	3.148	3.917
90˚C/21 day	4.100	3.926	4.057
90˚C/28 day	4.121	4.139	4.021

A comparison between the results of immersion at ambient temperature and at 90˚C is helpful in determining the effect of elevated temperature on water intake by polymer composites. As diffusion is a thermally activated process, an increase in temperature accelerates short-term diffusion and increases the diffusion coefficient. The water absorption of polymer composites is strongly dependent on temperature under the same exposure conditions. Water is absorbed mainly by the resin. The manufacturing quality of composite specimens has an important influence on absorption. Defects which exist in a composite material will considerably favour the absorption of water and accelerate material degradation. However, the monotonic trend on the water absorption graph suggests that material degradation is not a major factor.

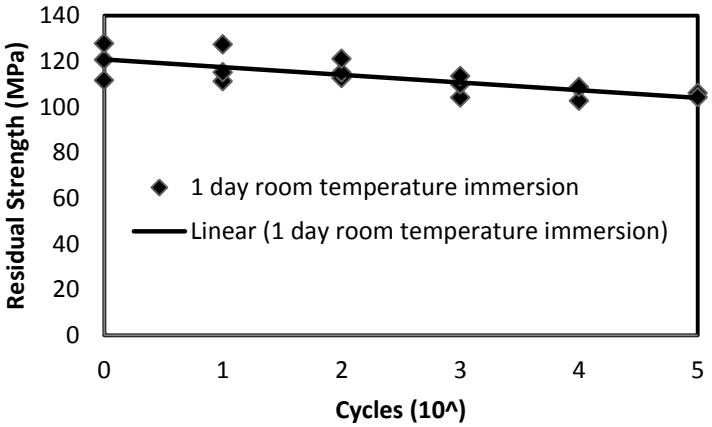
Temperature and Water Effect

The temperature and water effects on residual strength are demonstrated in Figures8-11. As seen in these figures, as cyclic loading progressed, decay in tensile residual strength was observed. Comparing the residual strength of chopped strand mat glass fibre/epoxy exposed to a humid environment at room temperature and at 90°C (Figure 10), the residual strength decreased at a rate of approximately 2.5% and 3.5% per log unit increase in the number of cycles. The average residual strength for each condition is summarised in Table 2. The greater strength degradation of specimens immersed at90˚Cwas due to the higher amount of water absorption and exposure to a higher temperature. According to Liu et al. (2002), this could be due to the weakening effects of higher thermal- and moisture-induced swelling stresses at the interface and/or matrix plasticisation. Plasticisation is known to be induced by water and high temperature (Schutte, 1994). It may also be hypothesised that this environment could result in either the breakdown of chemical bonds or secondary forces of attraction at the interface.

Table 2: Average residual strength of chopped strand mat glass fibre/epoxy with different temperatures and immersion durations

Conditions (immersion temperature/Days)	Fatigue cycles					
	10^0	10^1	10^2	10^3	10^4	10^5
Room temperature/1 day	119.97	117.86	116.23	109.10	106.53	109.79
Room temperature/7 days	112.08	116.78	114.26	109.64	109.39	109.36
Room temperature/14 days	107.07	111.49	110.63	107.61	104.66	108.16
Room temperature/21 days	111.02	112.19	109.70	105.97	101.46	99.18
Room temperature/28 days	108.32	105.81	108.12	105.98	106.37	100.58
90˚C/1 day	108.22	108.08	114.86	109.31	109.31	105.29
90˚C/7 day	103.88	111.36	101.88	101.83	99.77	99.27
90˚C/14 day	99.01	97.99	96.81	94.38	86.49	85.42
90˚C/21 day	94.16	92.91	91.17	82.39	80.96	85.29
90˚C/28 day	78.84	85.09	84.96	82.54	76.74	75.34

Therefore, the residual strength of the glass fibre/epoxy was more affected by hygrothermal ageing at a higher conditioning temperature and with a longer exposure time (i.e. more absorbed water). A comparison of the figures strongly indicates that water content is one of the key factors in the degradation of polymer composite residual strength. Water absorption can be detrimental to the residual strength of chopped strand mat glass fibre/epoxy.



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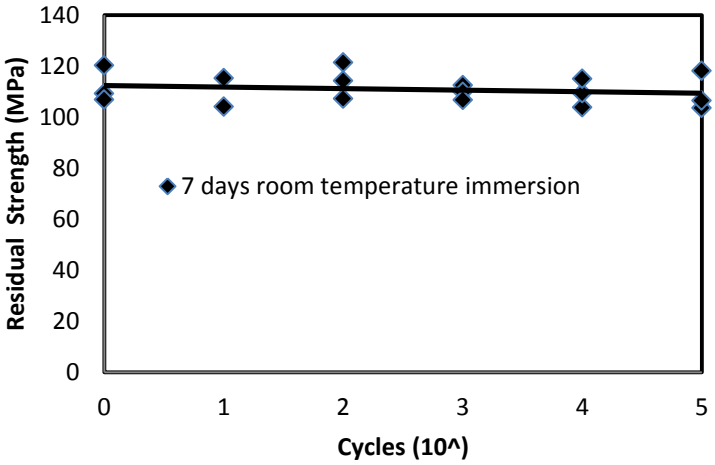

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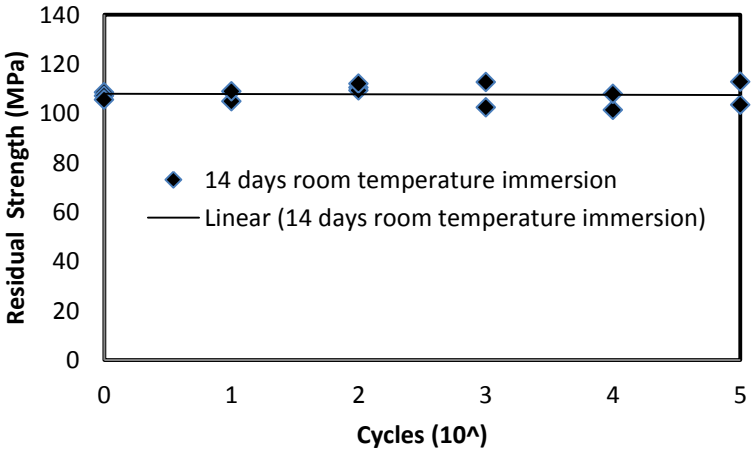
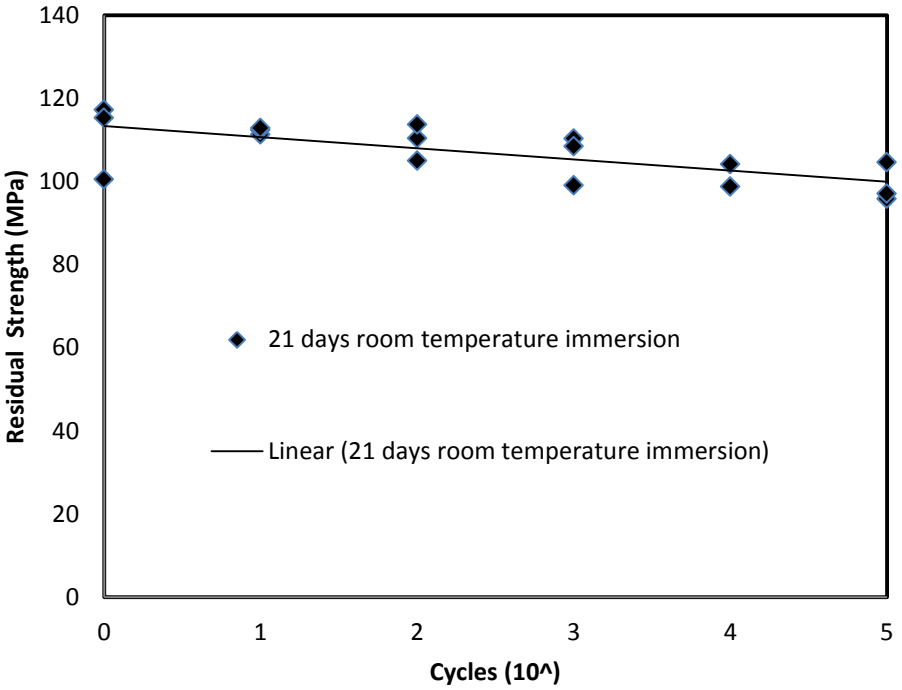


(c)

Figure 8. Residual strength curves of chopped strand mat glass fibre/epoxy after immersion at room temperature for 1,7 and 14 days



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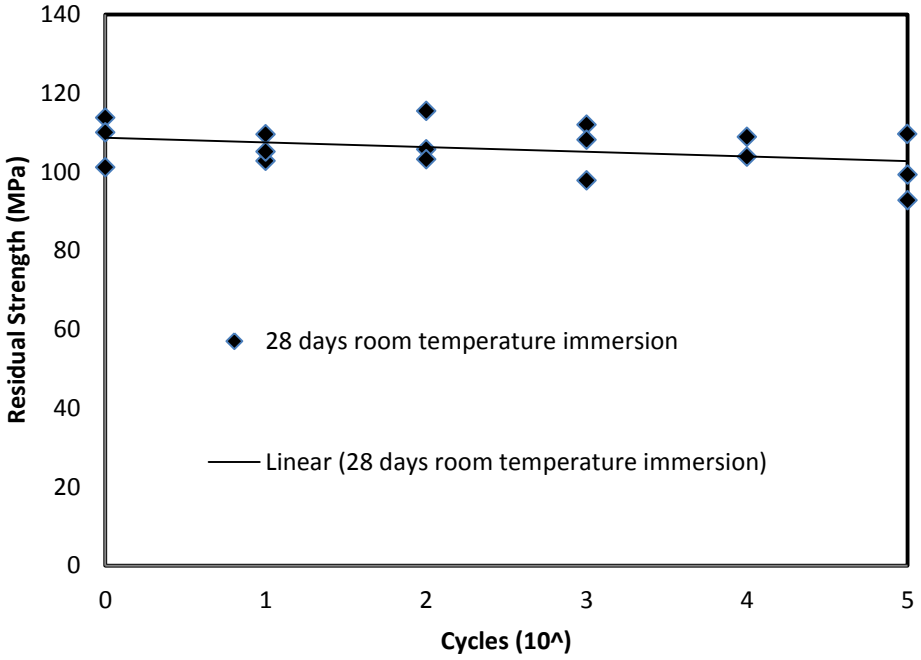

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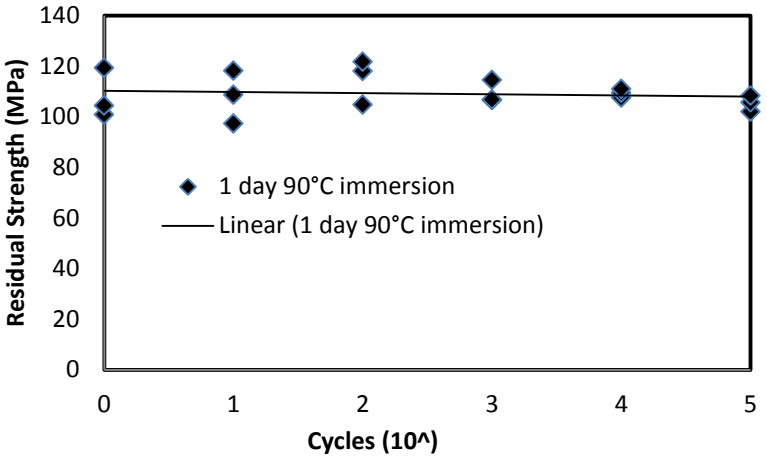
Figure 9. Residual strength curves of chopped strand mat glass fibre/epoxy after immersion at room temperature for 21and 28 days



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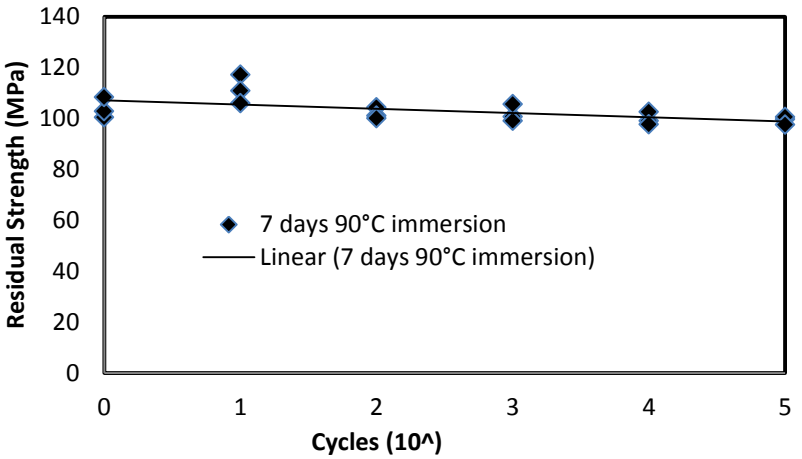

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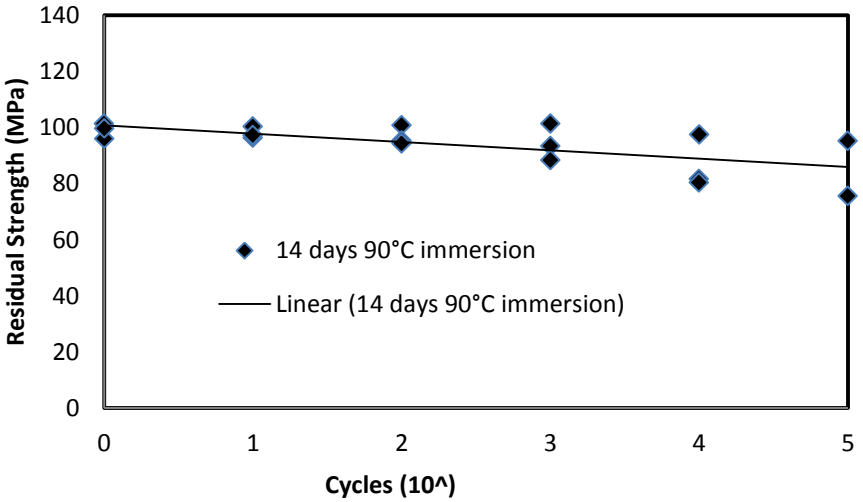


Figure 10. Residual strength curves of chopped strand mat glass fibre/epoxy exposed to a humid environment at 90°C for1, 7 and 14days

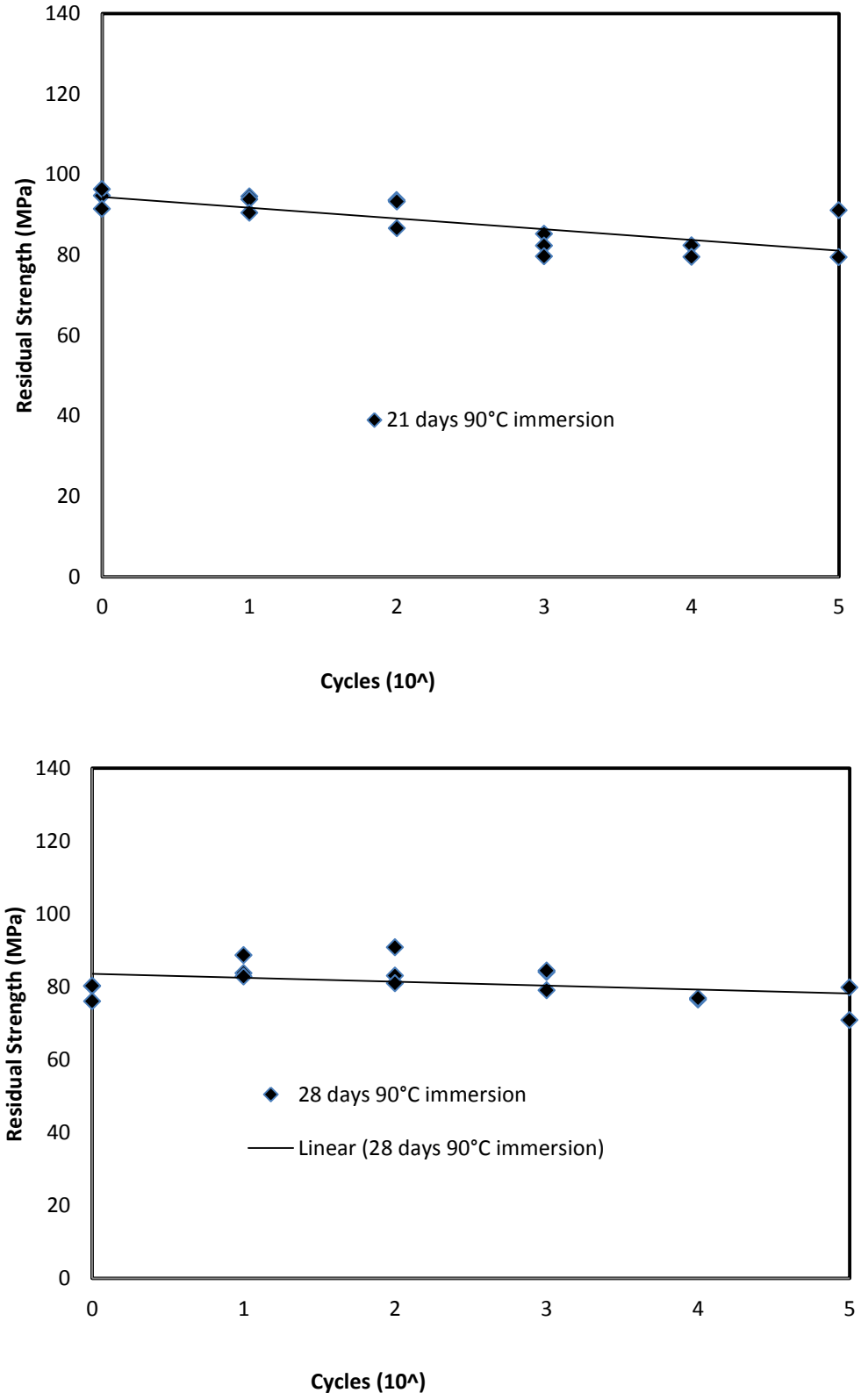
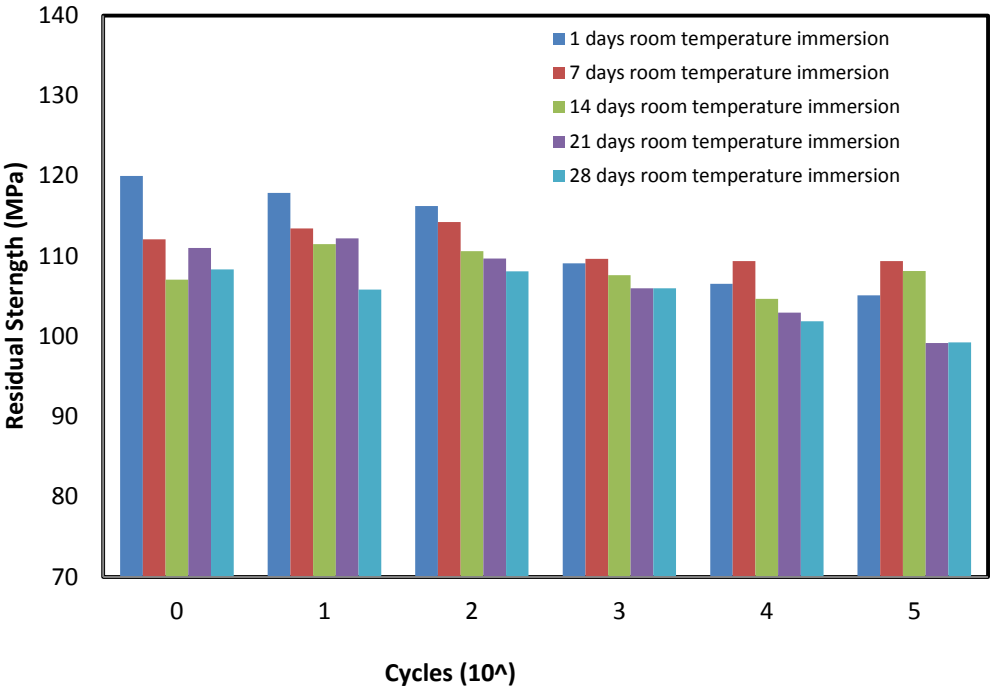


Figure 11. Residual strength curves of chopped strand mat glass fibre/epoxy exposed to a humid environment at 90°C for 21 and 28 days



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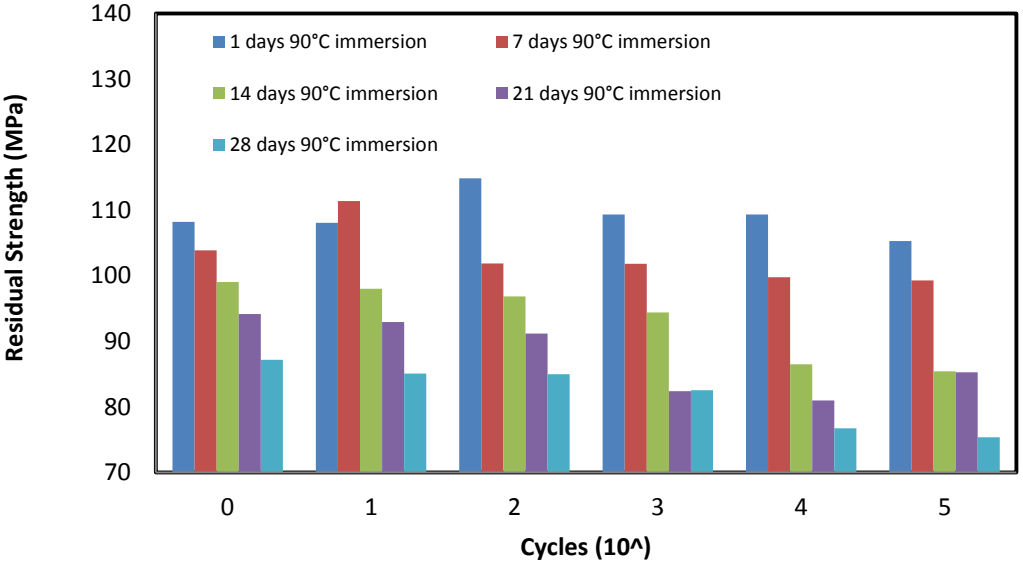

(b)

Figure 12. Comparison between residual strength curves for chopped strand mat glass fibre/epoxy tested exposed to a humid environment for different periods of time and at different temperatures

CONCLUSIONS

These experiments were carefully conducted to determine the variation in the residual strength of chopped strand mat glass fibre/epoxy due to changes in temperature and the interactive environment of variable temperature and moisture. The results obtained from this study clearly show that the properties of the glass fibre/epoxy deteriorate with exposure to high temperatures and water. The main conclusions which can be deduced from this study are as follows:

i. Chopped strand mat glass fibre/epoxy has highly consistent mechanical properties with a standard deviation of 6MPa for the residual strength under fatigue loading.
ii. The chopped strand mat glass fibre/epoxy composite follows an almost linear reduction in its fatigue residual strength with fatigue cycles. The degradation of glass fibre/epoxy residual strength in the temperature range from room temperature to90°C was only about 10%.
iii. It appears that for chopped strand mat glass fibre/epoxy, with increased immersion temperature and immersion time, the water content increases. The water intake of polymer composites is strongly dependent on temperature at the same relative humidity.
iv. The residual strength of the glass fibre/epoxy is influenced by hygrothermal ageing at elevated temperature and with longer exposure times (i.e. more absorbed water).
v. The chopped strand mat glass fibre material has high resistance to tension-tension fatigue loading, as the residual strength is reduced only slightly with an increase in fatigue cycles.

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