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LIFE ASSESSMENT AND PREDICTION

Environmental Degradation of Unidirectional Polymer Matrix Composites: An Interim Report

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Environmental Degradation of Unidirectional Polymer Matrix Composites: An Interim Report

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ABSTRACT

This report provides an interim assessment of accelerated test methods evaluated within the Composites Performance and Design (CPD) Project "Life Assessment and Prediction" for characterising long-term properties and residual life/strength of glass and carbon fibre-reinforced composites exposed to aggressive environments and static loads. The report considers convenient methods for obtaining basic strength-time data for unconditioned and moisture conditioned fibre bundles and continuous aligned fibre-reinforced rods and laminates. These test methods require relatively short conditioning times and relatively low manufacturing and testing costs in comparison with current practices.

The report considers: (i) tensile testing of moisture pre-conditioned fibre bundles and glass fibre-reinforced polyester rods; (ii) static fatigue testing of unconditioned glass fibre bundles and unidirectional glass fibre-reinforced rods and laminates; (iii) flexural properties of moisture pre-conditioned unidirectional laminates at ambient and elevated temperatures; and (iv) autoclave conditioning of flexural specimens manufactured from carbon fibre-reinforced laminates. Moisture pre-conditioning involved immersion in deionised water at elevated temperatures ranging from 23 ^{o}C to 70 ^{o}C for up to 42 days, whereas autoclave conditioning involved exposure of composite specimens to a steam environment at 136 ^{o}C and 2.2 bar for periods no longer than 24 hours.

The principal conclusions that can be drawn from the results to-date are: (i) fibre tows and small diameter (i.e. 1.5 mm) composite rods are suitable for accelerated testing under combined static loads and hostile environments with fibre tows offering a relatively rapid method for evaluating fibre sensitivity to chemical attack; (ii) transverse flexural properties are particularly sensitive to the combined effect of moisture and elevated temperature; and (iii) autoclave conditioning can accelerate moisture absorption by a factor of 100 and is suitable for use with materials designed for hot/wet conditions. The report provides a summary of the results, including recommendations on preparation and testing of fibre bundles and composite rods, and concludes with comments relating to future work.

The report was prepared as part of the research undertaken at NPL for the Department of Trade and Industry funded project on "Composites Performance and Design - Life Assessment and Prediction".

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1. INTRODUCTION

This report provides an interim assessment of techniques that can be employed to accelerate environmental degradation in glass and carbon fibre-reinforced composites. The research described in this report forms part of the DTI funded project "Composites Performance and Design (CPD2) "Life Assessment and Prediction" directed towards the development and validation of test methods and predictive models that can be used for characterising polymer matrix composites (PMCs) exposed to combined aggressive environments and applied loads. The report considers test methods for obtaining basic strength-time data for unconditioned and moisture conditioned fibre bundles and continuous aligned fibre-reinforced rods and laminates.

The report is divided into six sections including the introduction (Section 1). Section 2 describes the materials used to validate the test methods in this programme, specimen geometry and specimen preparation. Tensile test results for moisture pre-conditioned fibre bundles and glass fibre-reinforced polyester rods are presented in Section 3. Section 4 considers static fatigue testing of unconditioned glass fibre bundles and unidirectional glass fibre-reinforced rods and laminates. The combined effect of temperature and moisture on the flexural properties of unidirectional laminates is evaluated in Section 5. This section also examines the use of a high temperature and pressure autoclave as a means of inducing accelerated moisture degradation. Conclusions and recommendations for future work are given in Section 6. **Throughout this report, statements of particular importance or relevance are highlighted in bold type**.

2. MATERIALS CHARACTERISATION

2.1 MATERIALS DESCRIPTION

The materials used to develop and validate the test methods in this programme are listed below:

(a) E-glass (1,878 Tex or g/km) fibre tows supplied by RBJ.

(b) Pultruded glass fibre-reinforced polyester rods (glass/polyester). The composite consisted of axially aligned E-glass fibres impregnated with Scott Bader Crystic 196 orthophthalic polyester. Rods of 1.5 mm, obtained from RBJ, were tested. The rods were post cured for 3 hours at 80 °C

(c) Autoclave compacted continuous unidirectional glass fibre-reinforced epoxy prepreg sheet (E-glass/Fibredux F922). Laminates were manufactured at the National Physical Laboratory (NPL) to Hexcel Composites specifications. The laminates were also post-cured to the pre-preg suppliers specifications.

(d) Autoclave compacted continuous unidirectional glass fibre-reinforced epoxy prepreg sheet (E-glass/Fibredux 913). Laminates were manufactured at NPL to Hexcel Composites specifications.

(e) Autoclave compacted continuous unidirectional carbon fibre-reinforced epoxy prepreg sheet (Torayca T300/Fibredux 924). Laminates were manufactured (including post curing) at NPL to Hexcel Composites specifications.

On delivery, all rods and panels were visually inspected for evidence of damage or processing defects.

2.2 FIBRE CONTENT AND COMPOSITE DENSITY

Fibre volume fraction, $\mathbf{V}_f$ fibre weight fraction, $\mathbf{W}_f$, and composite density, ρ_f, were measured for all materials (Table 1). Composite density measurements were carried out using method A (zeroed pan immersion) specified in ISO 1183 [1]. Fibre volume and weight fraction measurements for the glass fibre-reinforced rods and laminates were carried out according to the ISO 1172 standard [2], which uses a resin burn-off technique. In this technique, the composite is dried to constant weight mass then exposed to 600 °C in a furnace for at least an hour to remove all traces of resin. The fibre volume and weight fractions of unidirectional carbon-fibre/epoxy panels were determined according to BS ISO 11667 [3]. Resin removal was achieved using concentrated sulphuric acid and hydrogen peroxide. This process was carried out using a Prolabo Microdigest 401 digester.

Table 1 Composite Density, Fibre Volume Fractions and Fibre Weight Fractions

Material	Composite Density (kg/m^3)	Volume Fraction (%)	Weight Fraction (%)
E-glass/polyester	1,862 ± 21	50.56 ± 1.10	69.50 ± 0.56
E-glass/F922	2,122 ± 53	65.41 ± 4.46	78.84 ± 3.01
E-glass/913	1,883 ± 39	50.95 ± 0.19	69.26 ± 0.26
T300/924	1,555 ± 10	61.49 ± 1.44	68.48 ± 1.24

2.3 SPECIMEN GEOMETRY AND PREPARATION

This section describes the test methods and specimen geometries used for testing fibre tows, composite rods and unidirectional laminates. Details of specimen preparation for each method are also covered in this section.

2.3.1 Fibre Bundles

Tensile and static fatigue (tension-tension) tests were carried out on unimpregnated E-glass fibre tows using the specimen geometry shown in Figure 1.

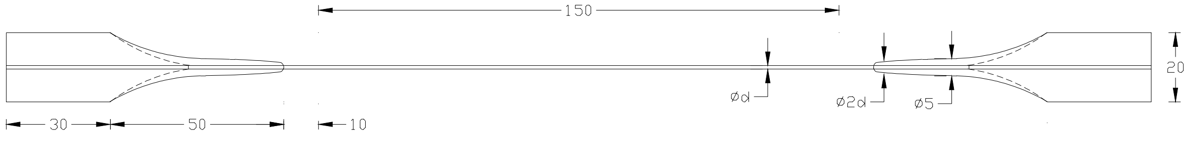

Figure 1 Fibre tow test specimen (mm).

Specimen preparation was carried out according to BS ISO 9163 [4]. A cold-curing epoxy system based on Araldite® LY 5052/hardener HY 5052 (Ciba Speciality Chemicals) was used to produce the end tabs. The end tabs were cast in modified moulds, using BS ISO 9163 specifications as a guide, and cured at 80 °C for 20 minutes. **It is important that the resin**

system has low viscosity to ensure full impregnation of the fibres within the tab region and good mechanical and dynamic properties.

2.3.2 Composite Rods

The test geometry specified in BS ISO 9163 proved unsatisfactory for measuring the tensile strength of composite rods with diameters of 1.5 mm or greater. It was found that the interface between the composite rod and epoxy resin end tabs yields/failed prematurely; resulting in pull-out of the composite rod rather than tensile failure within the gauge-length. As a result, a new method was developed for producing end tabs for the composite rods. Figure 2 shows a schematic of the composite rod specimen and end tab used for testing glass/polyester pultruded rods with a nominal diameter of 1.5 mm.

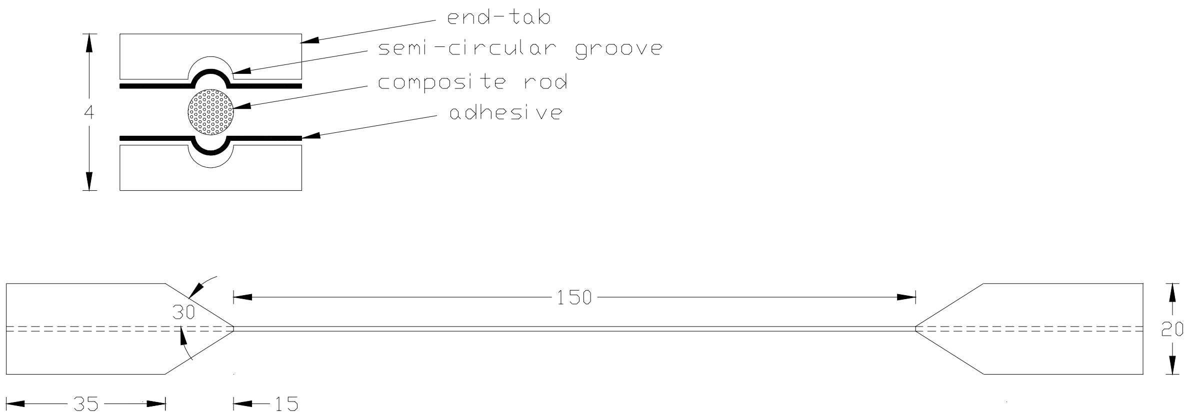

Figure 2 Composite rod specimen and end tab (mm).

The end tabs were manufactured from a plain woven glass fabric reinforced epoxy laminate (1.6 mm thick) with the fibre axes of the fabric set at ±45^{o} to the specimen axis. A high elongation adhesive was used to bond the end tabs to the specimen. **The use of a film adhesive to bond the end tabs was found to reduce both preparation time and adhesive wastage. Specimen preparation was also relatively clean in comparison to paste adhesives**. The semi-circular groove, shown in Figure 2, was cut with a 1.5 mm thick diamond slitting wheel (water lubricated).

The test geometry shown in Figure 2 is limited to rods with diameters of 1.5 mm or less. Testing of larger diameter rods required cylindrical moulded end tabs made with a high shear strength adhesive paste. Preliminary trials were carried out on 3 mm diameter rods using bonded end tabs that were 1.25 mm thick and 50 mm long. The trials proved successful with tensile failure consistently occurring within the gauge-length.

2.3.3 Unidirectional Laminates

Specimen preparation of unidirectional laminates was carried out to BS EN ISO 527-4 [5] specifications. Specimens were 250 mm in length, 15 mm wide and 1 mm (i.e. 8 plies) thick. The overall gauge-length (i.e. region between grips) was 150 mm. End tabs (50 mm long), manufactured from a plain woven glass fabric/epoxy laminate (1.6 mm thick) with the fibre axes of the fabric set at ±45^{o} to the specimen axis, were adhesively bonded to the specimens. The tab angle was 90^{o} (i.e. not tapered).

Narrow laminate strips, 3 mm wide and 2 mm (i.e. 16 plies) thick, were also tested. Apart from the differences in width and thickness, all other aspects of specimen geometry and preparation were the same as that for the standard test specimen.

3. TENSILE TESTS

This section presents the results from tensile tests that were carried out to evaluate the effects of exposure time and temperature on the residual strength of moisture pre-conditioned fibre bundles and glass/polyester rods. Specimens were immersed in deionised water at temperatures ranging from 23 ^{o}C to 70 ^{o}C. Batches of specimens were withdrawn at selected intervals over a 3 week period for the E-glass tows and over a 6 week period for the composite rods and then tested within an hour of removal from the water bath. The 6 week (≈ 1,000 hours) period was considered representative for the development of an accelerated ageing test programme. Testing was carried out under ambient conditions (i.e. 23 ^{o}C, 50% relative humidity) at a constant cross-head speed of 2 mm/min using an Instron 8501 servo-hydraulic test machine fitted with servo-hydraulic grips. Instron Series IX software was used to control the servo-hydraulic test machine and to collect the test data. Five specimens per condition were tested.

3.1 FIBRE BUNDLES

The stress rupture (i.e. maximum load at failure) of unconditioned and moisture degraded E-glass fibre tows was determined using BS ISO 9163. The results obtained are shown in Figure 3, and Tables 2 and 3. The maximum load at failure, as shown in Figure 3, has been normalised with respect to the ultimate tensile load of dry (i.e. unconditioned) fibre tows, which was measured at the same displacement rate. A number of observations can be made in relation to the environmental resistance of E-glass fibre tows exposed to the combined effect of temperature and moisture.

- **Tensile strength decreases linearly with exposure time, with a 50% reduction in strength occurring within 3 weeks**
- **Degradation mechanism is essentially temperature independent.**
- **Tensile modulus of E-glass fibre tows remains unaffected by water immersion at elevated temperatures.**

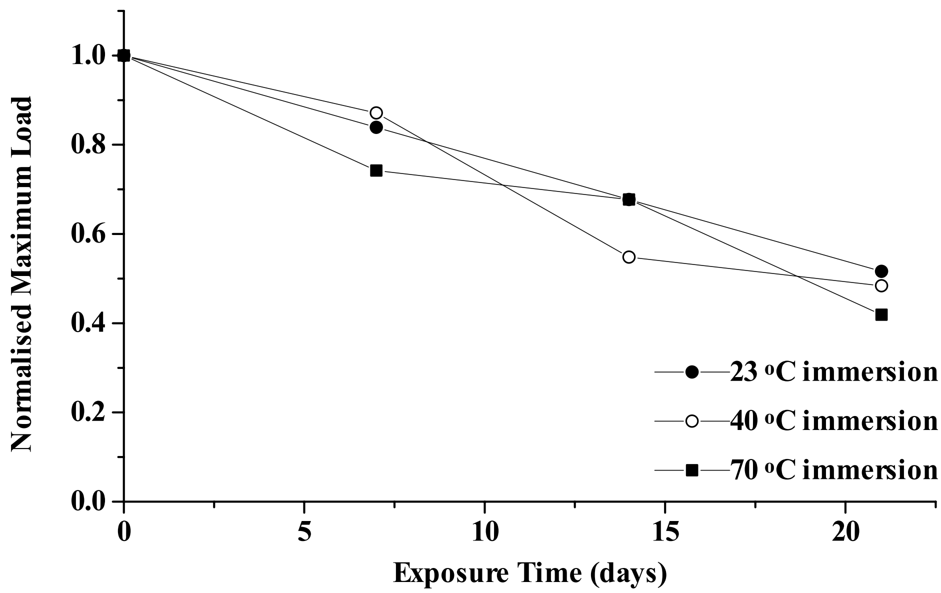

Figure 3 Maximum load at failure for moisture pre-conditioned E-glass fibre tows.

Table 2 Tensile Results for Unconditioned E-Glass Fibre Tows

Property	Measured Value
Breaking Stress (N/Tex)	0.31 ± 0.04
Breaking Strain (%)	2.11 ± 0.14
Tensile Modulus (N/Tex)	18.3 ± 0.5

Table 3 Rupture Stress (N/Tex) for Moisture Pre-conditioned E-Glass Fibre Tows

Exposure Time (days)	Pre-Conditioning Temperature (°C)		
	23	40	70
7	0.26 ± 0.02	0.27 ± 0.03	0.23 ± 0.02
14	0.21 ± 0.02	0.17 ± 0.01	0.21 ± 0.03
21	0.16 ± 0.01	0.15 ± 0.01	0.13 ± 0.02

The results in Figure 3 indicate that pre-soaking in the absence of stress had a severe effect on the subsequent short-term strength of the E-glass fibres. Degradation of the glass fibres can be mainly attributed to leaching of alkali oxides (sodium or potassium oxide) from the fibre surface resulting in the formation of surface micro-cracks. Checks need to be carried out to determine the degree of reversibility, chemical changes within the glass fibre due to environmental attack and the extent of micro-damage on the fibre surfaces. The results presented in this section clearly demonstrate that tensile testing of fibre tows offers a relatively quick and cost effective means of evaluating fibre sensitivity to chemical attack.

NB. Glass fibres are susceptible to damage induced through handling and moisture degradation and therefore care should be taken to avoid these problems. Glass fibres should be stored in a dry (i.e. low humidity) area.

3.2 COMPOSITE RODS

A series of tensile tests were conducted on pre-conditioned glass/polyester rods. Testing was conducted according to BS ISO 9163. The results, shown in Table 4 and Figure 4, indicate that, without applied stress, the rate of reduction in tensile strength of the glass/polyester rods increases with pre-conditioning temperature. The tensile strength, as shown in Figure 4, has been normalised with respect to the ultimate tensile strength of dry fibre tows measured at the same displacement rate (i.e. 1057 ± 16 MPa). The tensile modulus was found to be invariant with temperature and exposure time.

Table 4 Tensile Strength (MPa) for Moisture Pre-conditioned Glass/Polyester Rods

Exposure Time (days)	Pre-Conditioning Temperature (^oC)			
	23	40	60	70
7	958 ± 10	914 ± 21	629 ± 9	574 ± 79
14	869 ± 9	722 ± 82	524 ± 25	523 ± 12
21	798 ± 51	656 ± 24	460 ± 12	496 ± 24
42	751 ± 26	538 ± 19	468 ± 27	478 ± 27

The results clearly show that the Crystic 196 polyester resin offers minimal protection to the glass fibres when immersed in water at temperatures approaching the glass-transition temperature, **Tg**, of the dry resin (**Tg** = 63 ^oC). The effect of moisture content on the **Tg** for the polyester resin can be seen in Figure 5. It is recommended that the glass/polyester is not directly immersed in water at temperatures in excess of 40 ^oC.

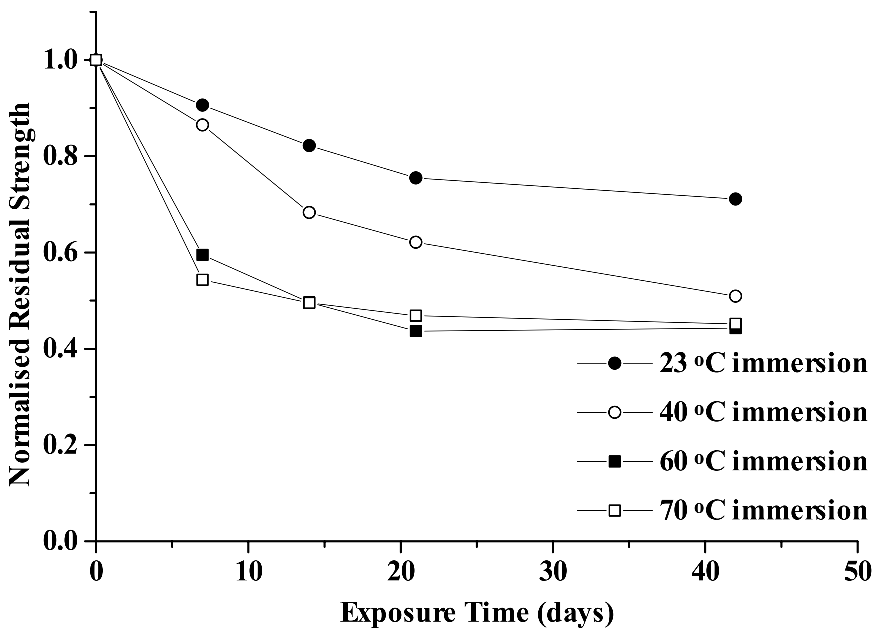

Figure 4 Tensile strength of glass/polyester for different preconditioning temperatures.

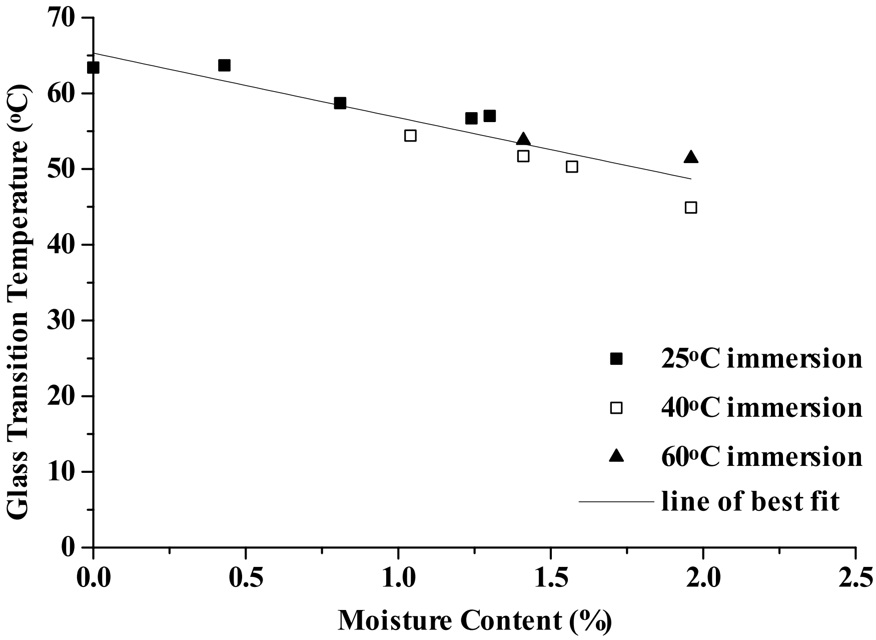

Figure 5 Glass transition temperature for moisture conditioned Crystic 196 polyester.

It can be concluded that small diameter rods (e.g. 1.5 mm) enable rapid uptake of aggressive agents, with any degradation effects on the composite being quickly manifested (within 7 days) in terms of strength reduction.

4. STATIC FATIGUE

This section presents the results from static fatigue tests that were carried out on E-glass fibre tows, glass polyester rods and unidirectional E-glass/F922 laminates (3 mm and 15 mm wide). The test results (Figures 6 to 9) presented in this report are confined to ambient conditions only. Testing is underway into evaluating the combined effect of environment and applied static tensile stress. These tests are being carried out using a bank of small creep machines, with the loading chain consisting of a screw jack in series with a load cell. The specimen is fully encapsulated in the liquid environment. The system developed at the National Physical laboratory (NPL) allows for the liquid environment to be circulated.

Most of the static tests under ambient conditions were carried out using Instron servo-hydraulic test machines. This is a relatively expensive option in comparison to the use of small stand alone test frames, but due to the relatively short duration of most of the tests it was expedient to use servo-hydraulic frames. **For short duration tests (i.e. static loads close to the maximum load at failure) load relaxation occurs and it is therefore necessary to continuously manually adjust the screw jack on the creep frame in order to maintain a constant load. The use of servo-hydraulic controls avoids this problem. Manually operated systems are best suited to long -term testing where loads are relatively low and load relaxation is minimal**.

The normalised stress rupture curves (Figures 6 to 9) when plotted on a linear-log plot can be approximated by a straight line fit as follows:

$$\sigma_{APP} / \sigma_{UTS} = 1 - k \log t_f \qquad (1)$$

where σ_{APP} is the applied load (or stress), σ_{UTS} is the maximum short-term strength of the unconditioned material, **k** is the slope and t_f is time to failure.

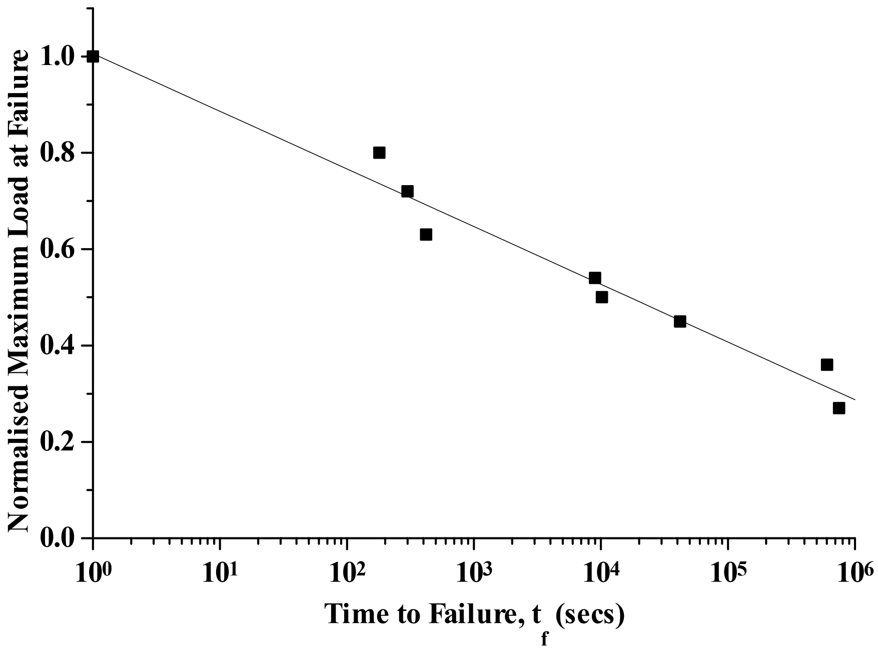

Figure 6 Stress rupture of E-glass fibres in air.

The rate of strength reduction was relatively high for the E-glass fibre tows (50% strength loss within 3 hours) as shown in Figure 6. In comparison, glass/polyester rods (Figure 7) and the 15 mm wide unidirectional E-glass/F922 specimens (Figure 8) are capable of sustaining a static load equivalent to 50% UTS for at least 4 months. The results for narrow (i.e. 3 mm wide) unidirectional E-glass/F922 (Figure 9) indicated that these specimens were less robust. Efforts were made to minimise the possibility of machine induced damage at the specimen edges affecting the strength results; particularly for the narrow strips. Although the narrow specimens were cut oversized and then polished to the final width, damage generally initiated at the edges. **The results from the 3 mm wide E-glass/F922 strips cannot be extrapolated to larger coupon specimens, whereas the results from the glass/polyester rods doe not preclude this possibility.**

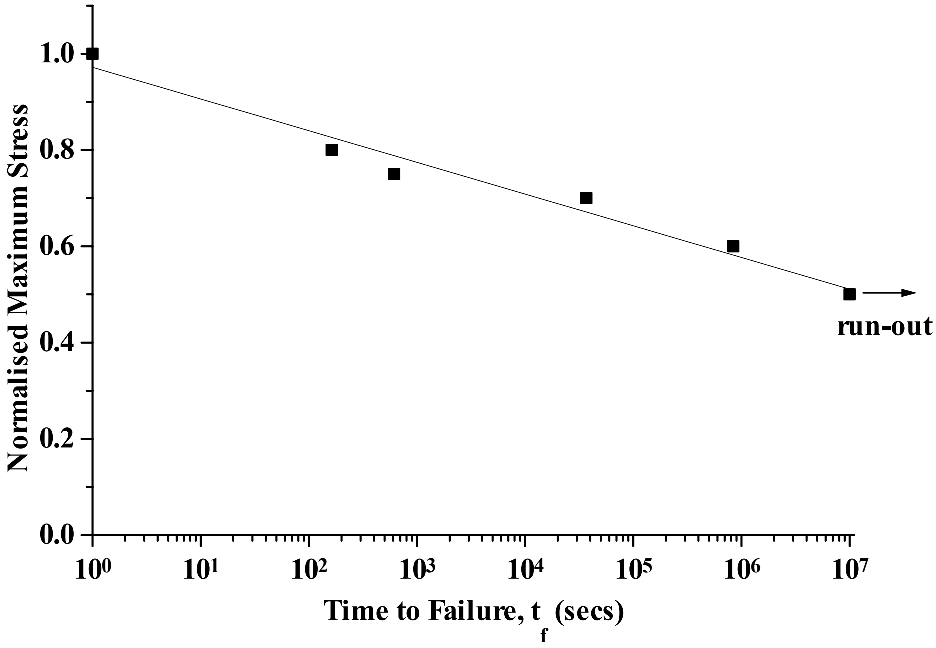

Figure 7 Failure stress of glass/polyester rods in air.

Glass fibre strands stress rupture under static loading conditions, whereas in the case of the composite rods and unidirectional laminates, failure was non-progressive (i.e. catastrophic) with failure consistently occurring within the gauge-length, although often near the end tabs. There was little indication on the load-displacement response that failure was imminent. Figure 10 shows a typical tensile failure for a glass/polyester rod specimen with fibre brushing.

Further static tests are to be carried out in aqueous environments (i.e. water, weak alkali and weak acid solutions). The results of both the ambient and environmental exposure tests are to be compared with predictive analysis, which is being carried out in parallel with the test programme.

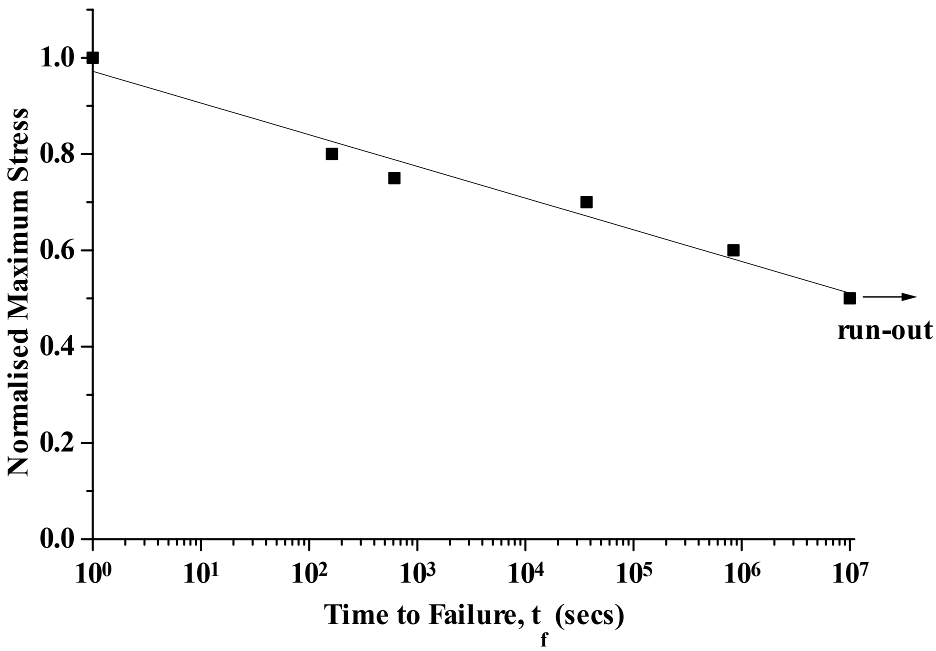

Figure 8 Failure stress of 15 mm wide unidirectional E-glass/F922 laminate in air.

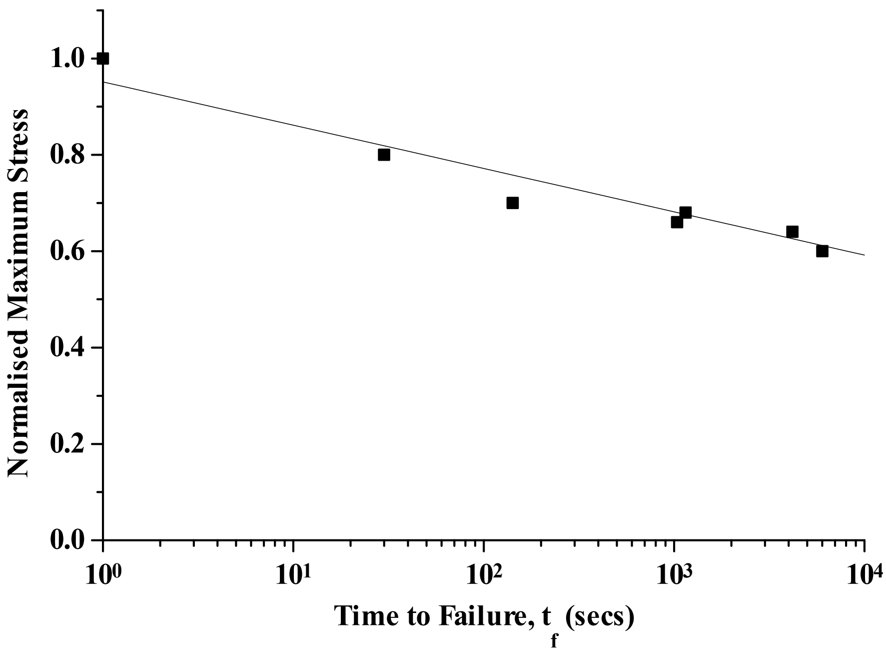

Figure 9 Failure stress of 3 mm wide unidirectional E-glass/F922 laminate in air.

Figure 10 Typical failure for glass/polyester rods

5. FLEXURE

5.1 HYGROTHERMAL EFFECTS

Flexure tests were carried out on unconditioned and moisture preconditioned flexure specimens cut from 2 mm thick unidirectional E-glass/913 and T300/924 laminates in both the longitudinal and transverse directions. The specimens were tested in four-point bending to BS EN ISO 14125 [6] specifications. An outer to inner span ratio of 3:1 was employed. The longitudinal and transverse specimens were 100 mm and 60 mm long, respectively. The width for both specimens was 15 mm. The flexural properties were measured at five temperatures (23 ^{o}C, 50 ^{o}C, 100 ^{o}C, 150 ^{o}C and 200 ^{o}C). Specimens were tested in an environmental chamber attached to an Instron 4507 screw-driven test machine. Temperatures were allowed to stabilise for 5 to 10 minutes prior to testing. Instron Series IX software was used to control the test machine and record load and strain during the tests. A 20 kN load cell was used to monitor load.

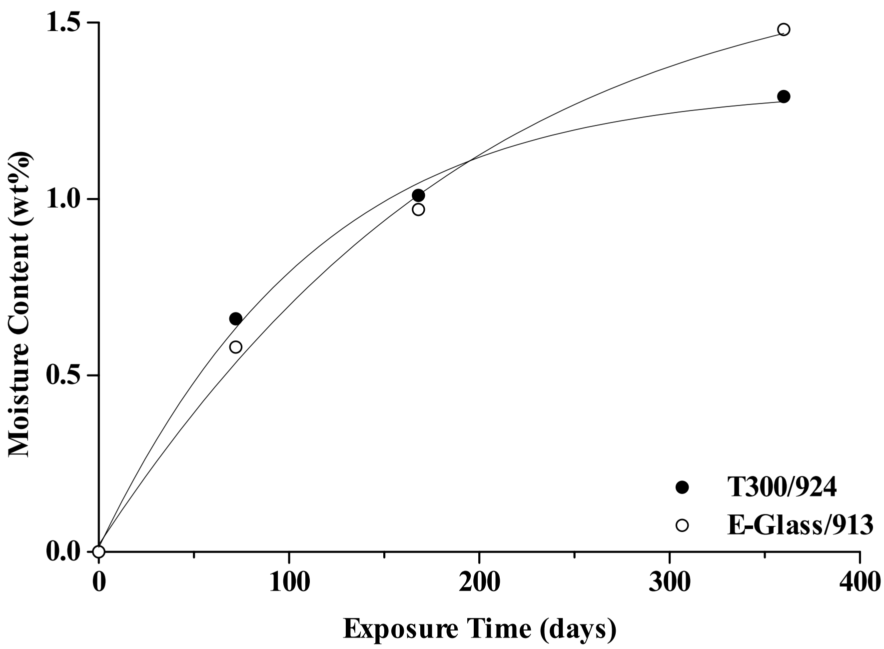

Figure 11 Moisture absorption of longitudinal E-glass/913 and T300/924 specimens.

The flexure specimens were immersed in deionised water at a temperature of 60 ^{o}C. Batches of specimens were withdrawn at selected intervals over a 15 day period and tested. Five specimens per condition were tested. The moisture content (wt%) was monitored using travellers (Figure 11) [7]. Dynamic mechanical thermal analysis (DMTA) measurements were carried out on moisture conditioned specimens to determine the change in **Tg** as a function of moisture content (Figure 12). ISO 6721-1 [8] specifies a method of using DMTA for plastics and composites.

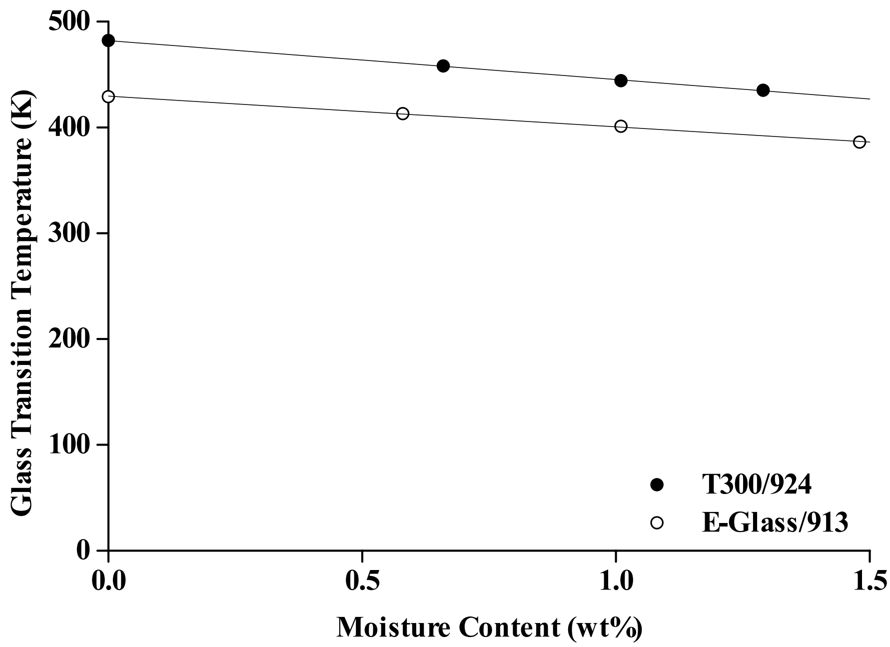

Figure 12 Glass transition temperature for moisture conditioned E-glass/913 and T300/924.

The transverse and longitudinal flexure results for the two composites are presented as a set of graphs (Figures A1 to A4) in the Appendix of this report. The following observations can be made in relation to flexure and moisture absorption results.

- **Tg** for both epoxy based composites decreases linearly with moisture content. The rate of decrease is approximately 29 ^{o}C/wt% for E-glass/913 and 37 ^{o}C/wt% for T300/924.
- Rate of moisture absorption was higher for the E-glass/913 laminate (Figure 11). A contributing factor was the higher resin content present within the composite.
- At elevated temperatures the adverse effect of moisture on the flexural properties is exacerbated. A synergism exists between moisture content and temperature.
- Transverse flexural properties are particularly sensitive to changes in moisture content.
- Flexural properties of E-glass/913 are more sensitive to changes in moisture and temperature in comparison with T300/924. This is understandable as the **Tg** for unconditioned (i.e. dry) E-glass/913 and T300/924 is 156 ^{o}C and 209 ^{o}C, respectively.
- **Transverse flexure tests offer a rapid and economic method of assessing environmental degradation. Tests can be carried out under combined environmental and applied loading (static and fatigue) conditions.**

- Strength and stiffness property reduction due to hygrothermal ageing can be "approximated" using the following simple algebraic relationship [9]:

$$\frac{P}{P_o} = \left(\frac{T_{gw} - T}{T_{gd} - T_o} \right)^{1/2} \quad (2)$$

where **P** denotes material property (e.g. longitudinal flexural strength) at the test temperature **T** (in K), **Po** is the initial property value of the dry material measured at ambient temperature **To** (296 K), and **Tgd** and **Tgw** are the glass transition temperatures of dry and conditioned (i.e. wet) material. The above equation results in conservative strength values. This relationship will only provide a rational solution when **Tgw > T** and **Tgd > To**.

The results further emphasise the need for models to predict hygrothermal degradation effects in composites. Work is being carried out within the CPD2 project to address this issue.

5.2 AUTOCLAVE CONDITIONING

Flexural properties have also been measured for autoclaved conditioned cross-ply (i.e. 0/90) T300/924 carbon/epoxy. Three-point flexure tests were carried out on dry and conditioned specimens under standard laboratory conditions according to BS EN ISO 14125. The flexure tests were simply trials to ascertain the effectiveness of using a steam autoclave to accelerate ageing. Specimens were exposed to the following high temperature and pressure conditions for periods ranging from 6 to 12 hours: (i) 1.05 bar and 121 °C; and (ii) 2.6 bar and 137 °C. The results of the tests are shown in Table 4. The specimens were conditioned in a commercial autoclave unit by LTE Scientific Ltd.

Table 4 Flexural Properties of Autoclaved Conditioned Cross-Ply T300/924 Carbon/Epoxy

Condition	Moisture Content (%)	Flexural Modulus (GPa)	Flexural Strength (MPa)
Dry	0.19 ± 0.01	92.5 ± 1.1	1332 ± 78
121 °C/1.05 bar/ 6 hrs	1.10 ± 0.02	90.9 ± 1.1	1,275 ± 73
121 °C/1.05 bar/ 12 hrs	1.43 ± 0.01	90.0 ± 0.9	1,198 ±97
137 °C/2.60 bar/ 12 hrs	2.19 ± 0.06	88.9 ± 0.9	1,223 ± 21

Trials have also been carried out using an in-house autoclave unit. The preliminary results showed that within 24 hours exposure at 3.3 bar and 137 °C the transverse tensile strength of unidirectional T300/924 had been reduced by 25%.

The results in Table 4 show that moisture uptake in 12 hours was approximately 2 wt%. The corresponding reduction in **Tg** was at least 52 °C. This is equivalent to immersing the specimens in water at 60 °C for approximately 1 to 2 months. Larger coupon specimens would take 3 to 4 months and real structures 1 to 2 years to condition using current procedures. **The results strongly indicate that autoclave conditioning is a viable option for inducing accelerated ageing, particularly for those systems possessing glass transition temperatures in excess of 120 °C to 140 °C. The technique may prove far too destructive for materials possessing a low Tg value, such as polyester resins. This promising accelerated ageing procedure warrants further consideration.**

6. CONCLUSIONS

A number of key points that have arisen from this work are summarised below.

Fibre Tows

- Glass fibres are susceptible to moisture degradation and therefore care should be taken to store fibre tows in a dry (i.e. low humidity) area. Tensile strength decreases linearly with exposure time in water (50% reduction within 3 weeks).
- Degradation mechanism due to water immersion is essentially temperature independent.
- Tensile modulus of E-glass fibre tows remains unaffected by water immersion at elevated temperatures.
- Fibre tows are suitable for accelerated testing under combined static loads and hostile environments offering a relatively rapid method for evaluating fibre sensitivity to chemical attack.

Composite Rods

- Small diameter (i.e. 1.5 mm) composite rods are suitable for accelerated testing under combined static loads and hostile environments. It may be possible to extrapolate static fatigue data to larger coupon specimens.

Unidirectional Laminates

- Results from the 3 mm wide E-glass/F922 strips cannot be extrapolated to larger coupon specimens.
- Transverse flexural properties are particularly sensitive to hygrothermal effects.
- Transverse flexure tests offer a rapid and economic method of assessing environmental degradation. Tests can be carried out under combined environmental and applied loading (static and fatigue) conditions.

General

- Stress rupture response with time can be "approximated" using Equation (1):

$$\sigma_{APP} / \sigma_{UTS} = 1 - k\log t_f$$

- Autoclave conditioning is a viable option for inducing accelerated ageing in PMCs.

Future work will consider:

- Environmental degradation of multidirectional laminates - evaluating methods for determining and predicting cumulative damage (e.g. stiffness loss and transverse matrix cracking). A number of conditions (e.g. water immersion, 50 ^{o}C/96% RH, skydrol and jet fuel) recommended by UK industry will be considered.
- Static fatigue testing of carbon and glass fibre tows and composite rods in aqueous environments (i.e. water, weak alkali and weak acid solutions). The results of both the ambient and environmental exposure tests are to be compared with predictive analysis.

- Environmental degradation of bulk resins (i.e. Fibredux F922 epoxy, Scott Bader Crystic 916 polyester and Norpol Dion 9100 vinylester).

ACKNOWLEDGEMENTS

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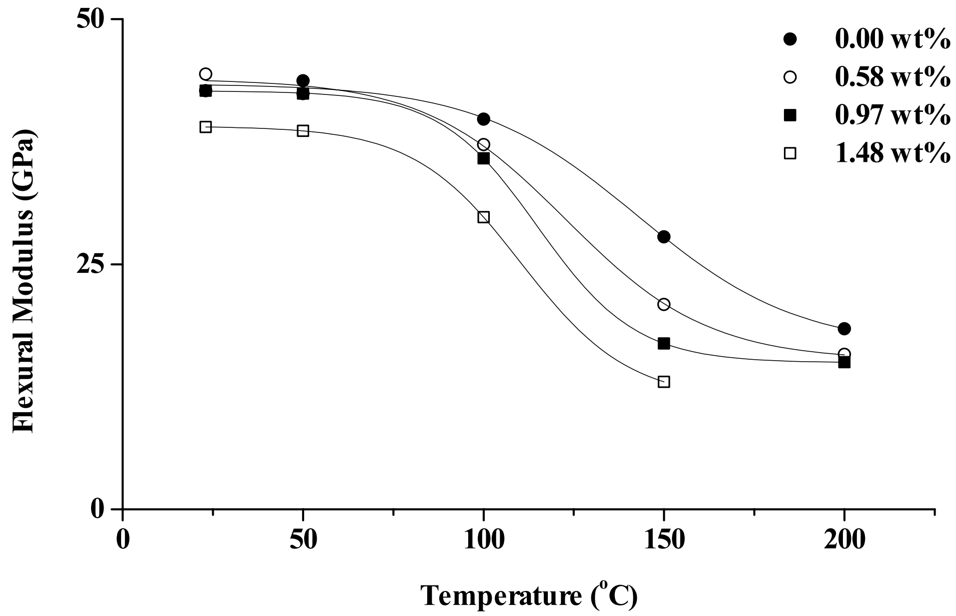
APPENDIX

HYGROTHERMAL EFFECTS ON FLEXURE PROPERTIES OF UNIDIRECTIONAL E-GLASS/913 AND T300/924



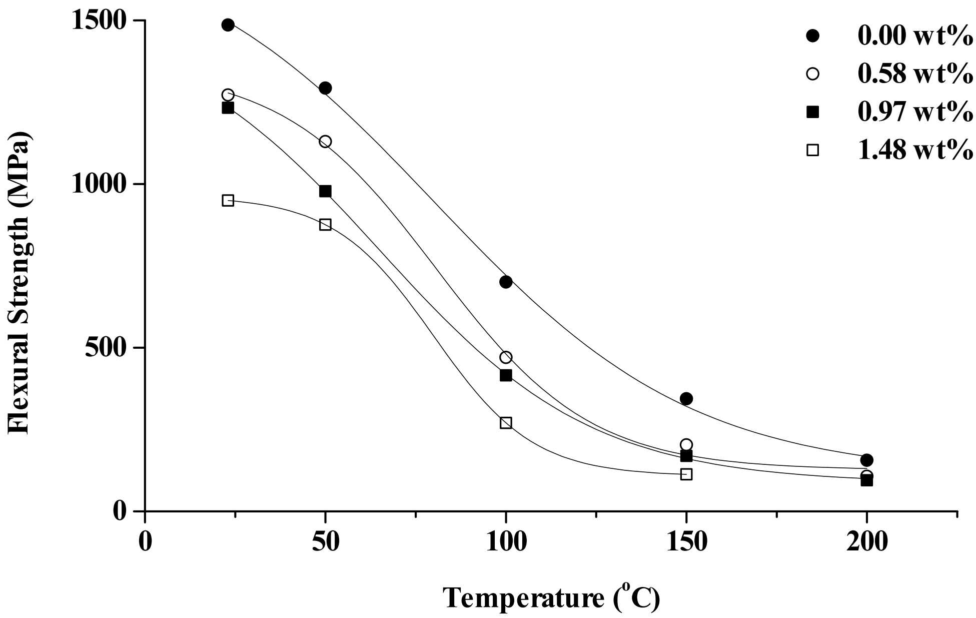
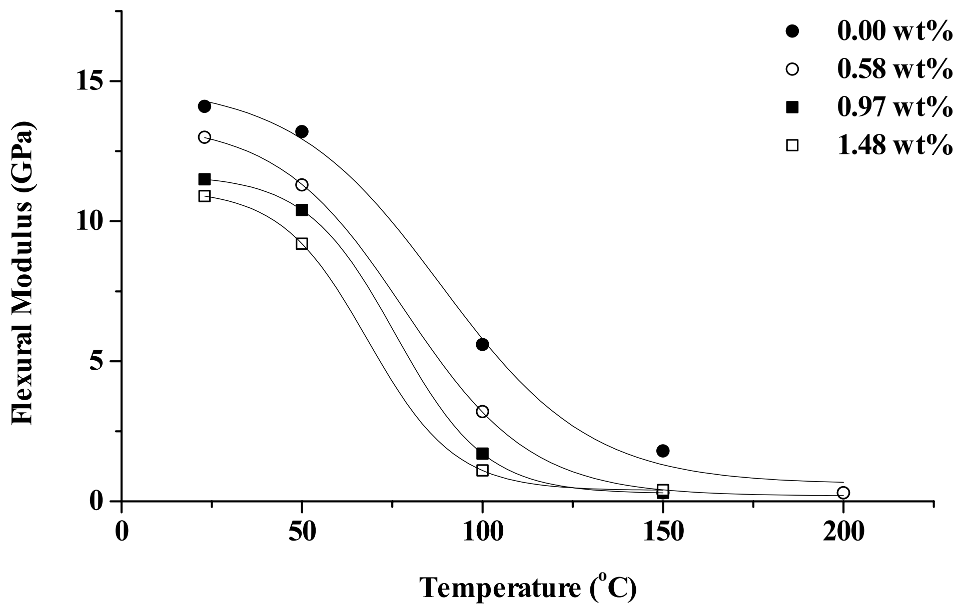


Figure A1 Longitudinal flexural properties of conditioned E-glass/913 with temperature.

APPENDIX (CONT.)

HYGROTHERMAL EFFECTS ON FLEXURE PROPERTIES OF UNIDIRECTIONAL E-GLASS/913 AND T300/924



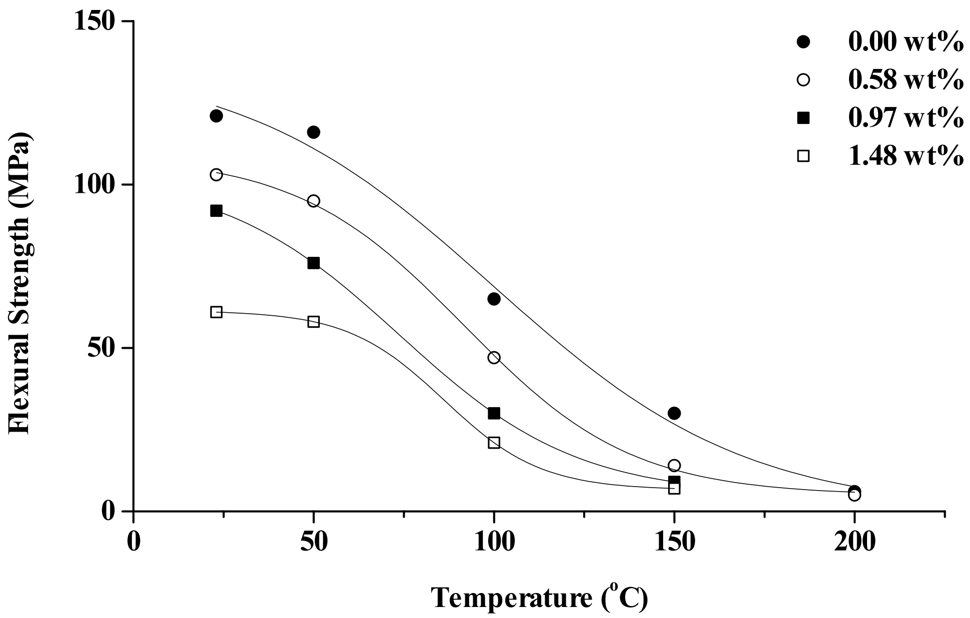
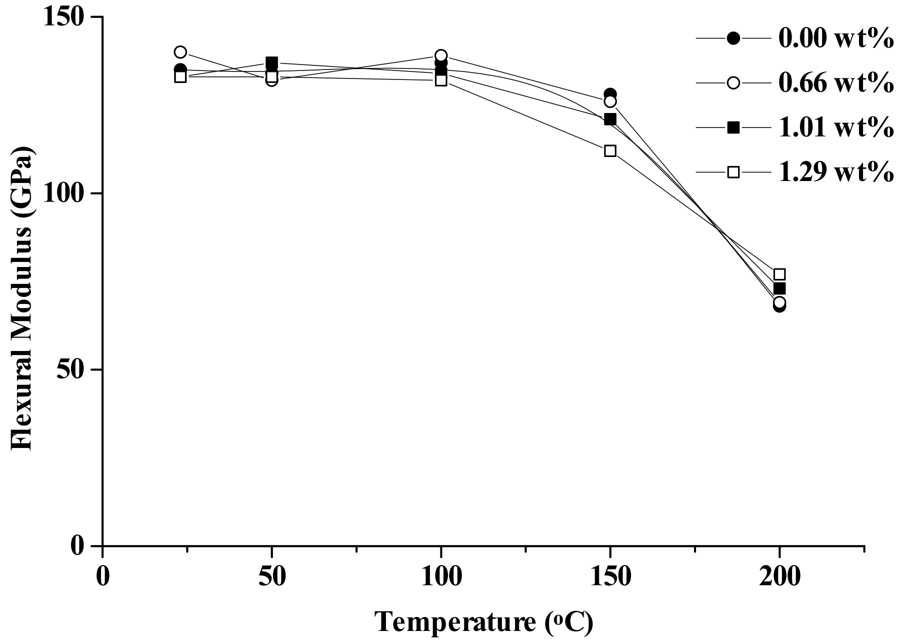


Figure A2 Transverse flexural properties of conditioned E-glass/913 with temperature.

APPENDIX (CONT.)

HYGROTHERMAL EFFECTS ON FLEXURE PROPERTIES OF UNIDIRECTIONAL E-GLASS/913 AND T300/924



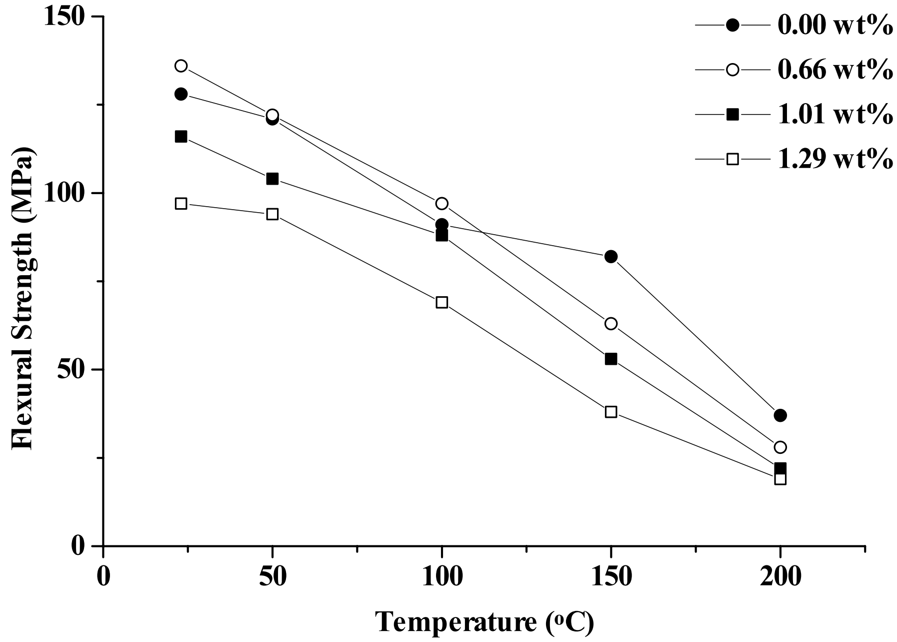


Figure A3 Longitudinal flexural properties of conditioned T300/924 with temperature.

APPENDIX (CONT.)

HYGROTHERMAL EFFECTS ON FLEXURE PROPERTIES OF UNIDIRECTIONAL E-GLASS/913 AND T300/924

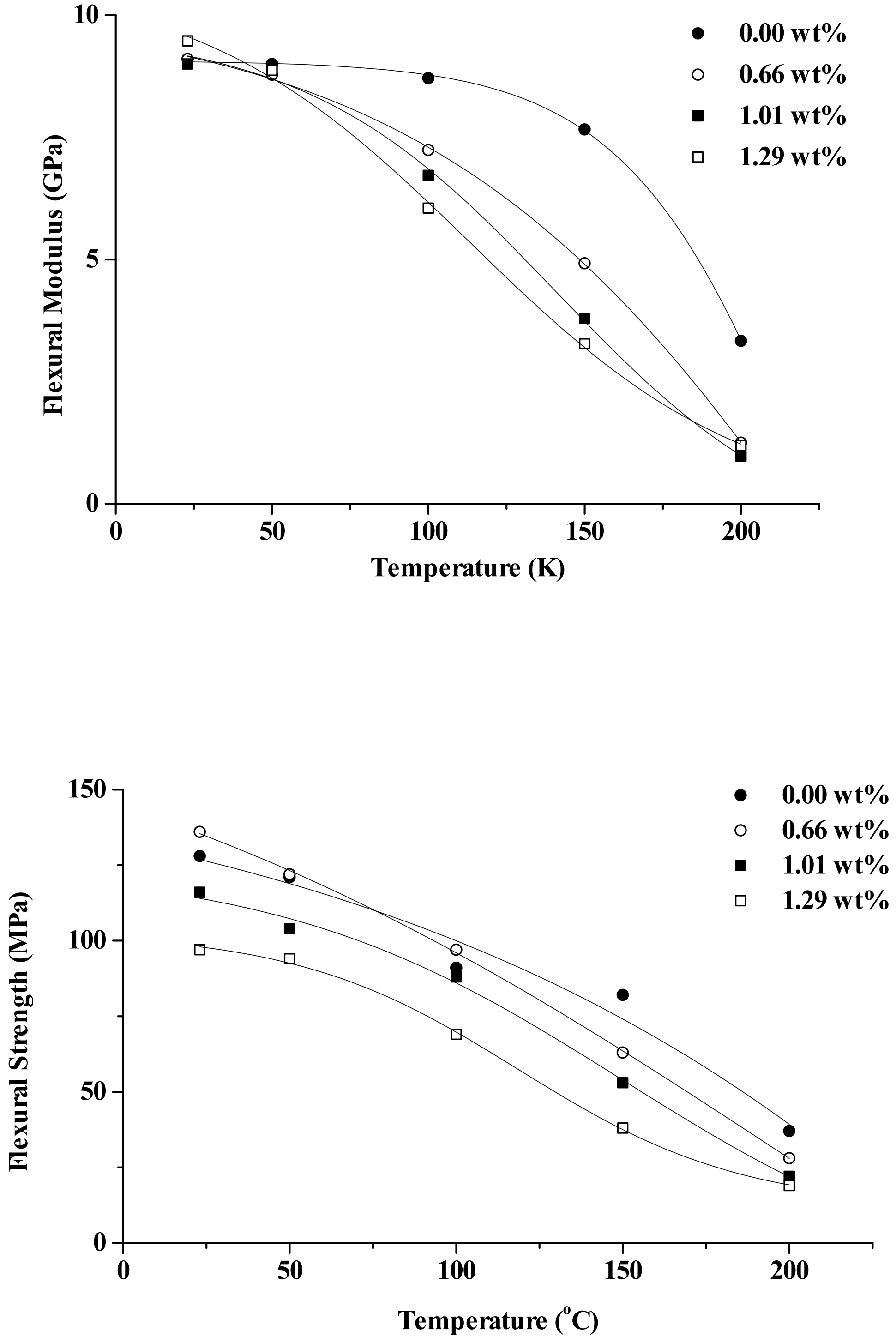


Figure A4 Transverse flexural properties of conditioned T300/924 with temperature.