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Impact of Hygrothermal and Loading Conditions on Apparent Diffusivity of GFRP Composites

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Abstract

Glass fibre-reinforced polymer (GFRP) has been used as an alternative to steel in concrete due to high strength-to-weight ratio, high stiffness-to-weight ratio, and corrosion and fatigue resistance. The main environmental factors for the deterioration of GFRP sandwich composites are temperature, sunshine, water/moisture, alkalinity and load. Most of the early durability tests were carried out with reference to application of FRP (Fibre Reinforced Polymer) in aerospace industries. Hygrothermal behaviour of preloaded sandwich structure immersed in water is examined herein. Moisture uptake was monitored for 50 days yielding percentage weight gain curves for samples of matrix (epoxy) and sandwich structure with different core thickness. The apparent diffusivity values extracted from the weight gain are significantly greater for initial days for greater core thickness sandwich structures.

Keywords: GFRP, composite, sandwich, polystyrene, apparent diffusivity

Introduction

Composites are a combination of 2 or more materials (reinforcing elements, fillers, and composite matrix binder), differing in form or composition on a macro scale. The constituents retain their identities, that is, they do not dissolve or merge completely into one another although they act in concert. The properties of a composite will be different from those of the constituents in isolation and set of performance characteristics is often greater than that of the components taken separately [1].

Composites can be classified in 2 ways, natural composites and man-made composites. Composites possess excellent strength and stiffness, they are very light materials, they possess high resistance to corrosion, chemicals and other weathering agents and they can be moulded to any shape and size with required mechanical properties in different directions. They also have high strength to weight ratio (low density high tensile strength) [2].

Fibrous composites, especially carbon fibre reinforced epoxy are increasingly being used in military and aerospace applications owing to several desirable properties including high specific strength, high specific stiffness and controlled anisotropy. Despite these advantages over conventional structural materials such as metals, composites are susceptible to heat and moisture when operating in harsh and changing environmental conditions. When exposed to humid environments, carbon-epoxy composites absorb moisture and undergo dilatational expansion.

When a fibre-reinforced composite material is exposed to a hygrothermal environment and mechanical loads, changes in material properties are expected. These changes in material properties are connected to an irreversible material degradation. The moisture may affect the laminates through chemical changes such as relaxation and oxidation of the matrix material. A cyclic moisture environment exposed to a laminate may cause damage such as *debonding* at the fibre/matrix interfaces and continuous

cracks. Other damage modes that can occur in a fibre-composite laminate are transverse matrix cracks, delamination and fibre fracture. The results of chemical changes and mechanical damage in general affect the overall material properties, e.g. elastic modulus, hygrothermal expansion coefficients, diffusion coefficients [3].

Usually one of the first observed damage modes in a laminated composite is *matrix cracking*. These cracks are in general not critical for final failure, but if they are connected to a surrounding moisture environment more rapid moisture absorption may be expected for the cracked laminate. The accelerated moisture absorption in a cracked material exposed to humid air is a result of the faster diffusion in air compared to the diffusion speed in the composite material. Faster moisture uptake may also result in faster material degradation [4]. This makes it important to know the moisture absorption behaviour in a cracked laminate. For an undamaged material, well-accepted moisture transportation models are available. The most common models for the transportation of moisture in undamaged polymeric composite materials are *Fickian diffusion and Langmuir diffusion*.

Environmental degradation and its impact on the performance and properties of the composites have been studied by various researchers. Mukherjee and Arwikar [5] have discussed structural scale tests on the synergistic effects of moisture, temperature, alkalinity and stress level on the performance and durability of GFRP sheet bonded externally on concrete. This paper describes the micro structural studies to find out the nature, quantum and mechanism of deterioration in the conditioned sheets.

Siriruk *et al*. [6] studied the effect sea environment on interfacial delamination behaviour of polymeric sandwich structures. Sandwich structures are utilized in naval craft and thereby are exposed to the sea water environment and temperature fluctuations over extended periods. The sandwich layup consists of a closed cell polymeric foam layer placed between thin carbon or glass fiber reinforced polymeric composite facings. Attention in this paper is focused on sea water effects on the interfacial mechanical response between foam and facing due to sustained sea water exposure using carefully controlled laboratory conditions.

Steeves and Fleck [7] analysed simply supported sandwich beams with composite faces and a PVC foam core subjected to 3 point bending. The faces comprise Hexcel Fibredux 7781-914G woven glass fibre-epoxy prepreg, while the core comprises closed cell Divinycell PVC foam of relative density 6.6 and 13.3 %. The mechanical properties of the face sheets and core are measured independently. A failure mechanism map was constructed to reveal the dependence of the dominant collapse mechanism upon the geometry of the beam.

Veazie *et al*. [8] experimentally investigate the facesheet/core interfacial fracture toughness of E-Glass/Vinylester facesheet, closed-cell polyvinyl chloride (PVC) core, sandwich composites. To determine the effects of a marine environment (temperature and sea water) on conditioned specimens with a crack present, an interfacial crack was induced prior, as well as subsequent to, 5000 h of elevated temperature (80 °C), elevated temperature and moisture (80 °C, 90 % + relative humidity), and sea-water (submersed) conditioning. Results showed that elevated temperature exposure contributes greatest to the PVC core degradation, whereas sea water exposure mostly degrades the facesheet/core interface. Exposure to elevated temperatures, along with inducing cracks between the facesheet and the PVC core degraded by elevated temperature exposure, appear to be the most detrimental to interfacial fracture toughness.

Aviles and Montero [9] experimentally evaluated the degradation of mechanical properties of E-glass/polyester facesheets bonded to PVC foam core using flexural testing of the laminates, through-thickness tension of the foam core and interfacial sandwich DCB fracture testing. Testing reveals substantial flexural stiffness and strength reductions for the laminated composites. Degradation of the interfacial face/core fracture toughness is weak for specimens subjected to elevated moisture and more pronounced for sandwich specimens immersed in sea water. After 30 days of exposure to high moisture, foam damage is visible in the form of cracks and pits on the cell walls. Optical examinations of expansional strains show that moisture absorbed by the foam penetrates only by about 2 - 3 mm from the core free surface in 95 % RH conditions, while it penetrates deeply in immersed conditions.

Wang *et al*. [10] performed quasi-static and low-velocity impact bending tests for sandwich beams with aluminium-foam core. The deformation and failure behaviour was explored. It was found that the

failure mode and the load history predicted by a modified Gibson's model agree well with the quasi-static experimental data. The failure modes and crash processes of beams under impact loading are similar to those under quasi-static loading, but the force-displacement history is very different. Hence the quasi-static model can also predict the initial dynamic failure modes of sandwich beams when the impact velocity is lower than 5 m/s.

Vaddadi *et al*. [11] used the heterogeneous characterization approach which incorporates 2 distinct features: transient moisture absorption analysis of actual composite materials exposed to a humid environment, and highly detailed computational analyses that capture the actual heterogeneous microstructure of the composite. The latter feature is carried out by modelling a uniaxial laminate having more than one thousand individual carbon fibres that are randomly distributed within an epoxy matrix. Results indicate that these computational models are essential in capturing accurate moisture absorption processes in actual specimens. In the analysis, the evolutions of thermal residual stresses and moisture-induced stresses within the humidity and thermal exposed composites have been analyzed. It was observed that high stress concentration develops in the epoxy phase where high fibre density or fibre clustering exists and its magnitude increases as the moisture content saturates. Large stresses can potentially initiate epoxy damage or delamination of epoxy and fibres. Furthermore, due to opposing effects of thermal and moisture exposure, lower stresses are found in the laminate when both are considered simultaneously.

In the present paper the effect of moisture & heat (i.e. hygrothermal effect) on the sandwich structure of Glass Fibre Reinforced Polymer (GFRP), woven fabric (E Glass) and thermocol (polystyrene) of different thickness was investigated and the changes in physical properties were considered. Diffusivity and percentage weight gain by the composite were taken as the responses for physical properties.

Experimentation and data calculation

The experimental setup was prepared with all the necessary inputs made. The aim of the experiment was to study the effects of environmental parameters and diffusivity, and percentage weight gain was measured for the composite sandwich material. Initially 40 samples were prepared and each sample was held in experimentation for pre-decided time periods then tested for their weight gain. A detailed test matrix is shown in the **Table 1**.

Setup

The setup basically consists of following main elements and pictorial view is shown in **Figure 1**:

- Water tank
- Heating elements
- RTD sensors
- Temperature controllers
- Solid state relays

Figure 1 Heating element and RTD sensor in a tank.

Specimen specifications

Front and top view of the specimen are shown in **Figure 2**. The following were the specifications of the sample:

Length of specimen	: 300 mm
Breadth of specimen	: 40 mm
Thickness of specimen	: t + 2h mm (approx.)

where t is thickness of the thermocol sheet and h is thickness of the glass fiber sheet.

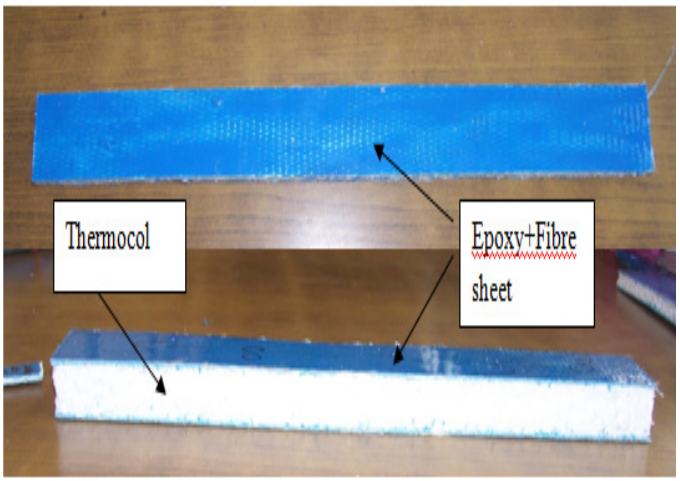

Figure 2 Actual image of the sample.

Table 1 Test matrix details (for weight gain).

Sandwich type	Bath temperature (°C)	Holding time (days)	No. of samples pre-stressed at % Load at failure (N)				Total samples
			Without load	30 %	50 %	70 %	
Sandwich with thermocol (8 mm thick)	45	10	1	1	1	1	4
		20	1	1	1	1	4
		30	1	1	1	1	4
		40	1	1	1	1	4
		50	1	1	1	1	4
Sandwich with thermocol (16 mm thick)	45	10	1	1	1	1	4
		20	1	1	1	1	4
		30	1	1	1	1	4
		40	1	1	1	1	4
		50	1	1	1	1	4

Results and discussion

Percentage weight gain by samples

The time variation of percentage weight gain (w_t) can be measured as;

$$w_t = \frac{W_t - W_0}{W_0} \times 100 \quad (1)$$

here W_t is the total weight after time t
W_0 is the reference dry weight of the specimen

Percentage weight gain of different core thickness and different loading samples with respect to time are shown below in **Table 2**.

Table 2 Percentage weight of different samples with respect to time.

Sandwich type	Bath temperature (°C)	Holding time (days)	No. of samples pre stressed at % Load at failure (N)			
			Without load	30 %	50 %	70 %
Sandwich with thermocol (8 mm thick)	45	10	0.204	0.223	0.151	0.087
		20	6.349	7.291	2.089	7.469
		30	7.109	7.690	2.162	7.744
		40	8.165	7.987	5.051	8.737
		50	9.755	10.342	9.286	9.705
Sandwich with thermocol (16 mm thick)	45	10	0.020	0.061	0.235	0.105
		20	7.224	5.008	3.577	6.484
		30	7.860	5.685	3.933	6.897
		40	8.296	6.094	5.150	7.607
		50	10.397	8.110	7.737	9.619

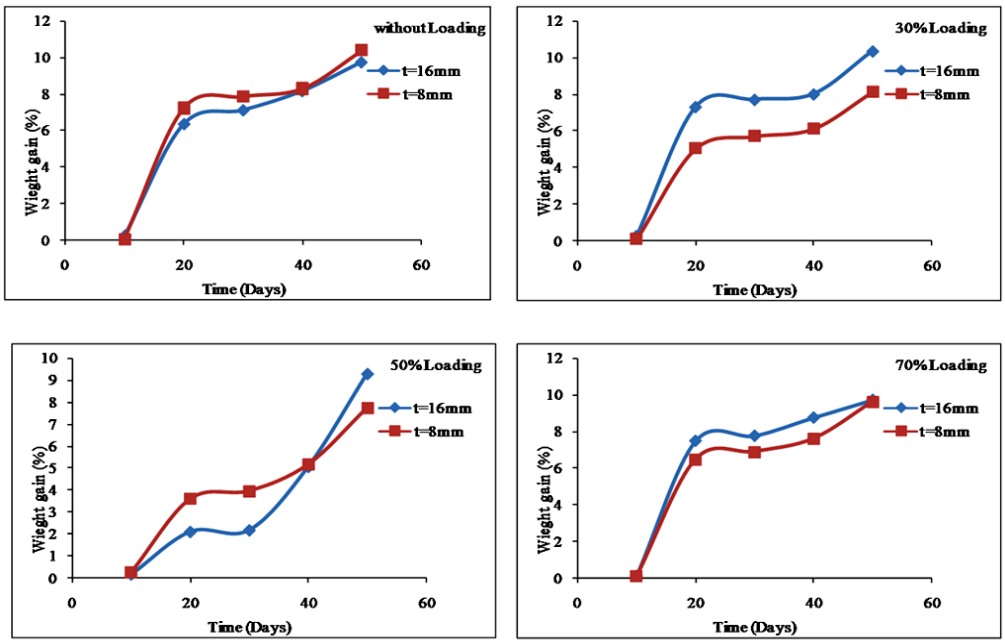

Figure 3 Percentage weight gain in samples with 8 and 16 mm core thickness after interval of 10 days for different preloading.

The percentage weight gain for each loading of both core thicknesses with respect to time are shown in the above graphs (**Figure 3**). The percentage weight gain (of moisture) was compared for different thickness and loading. It could be easily noticed that the percentage weight gain in both the core thickness is almost similar for increasing time.

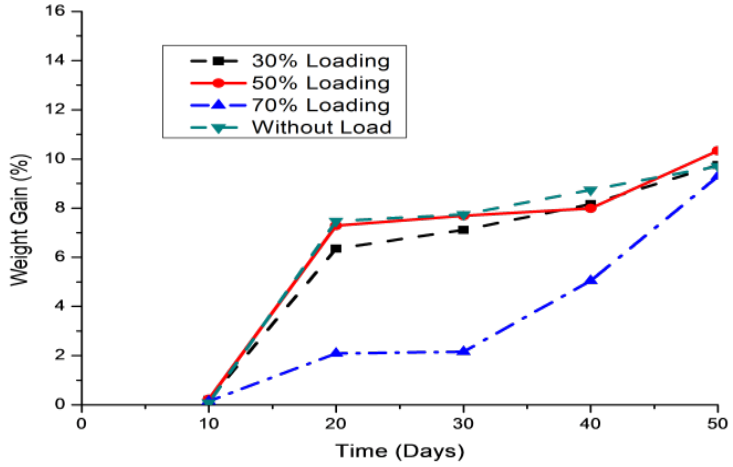

Figure 4 Percentage weight gain in samples of 8 mm core thickness after an interval of 10 days.

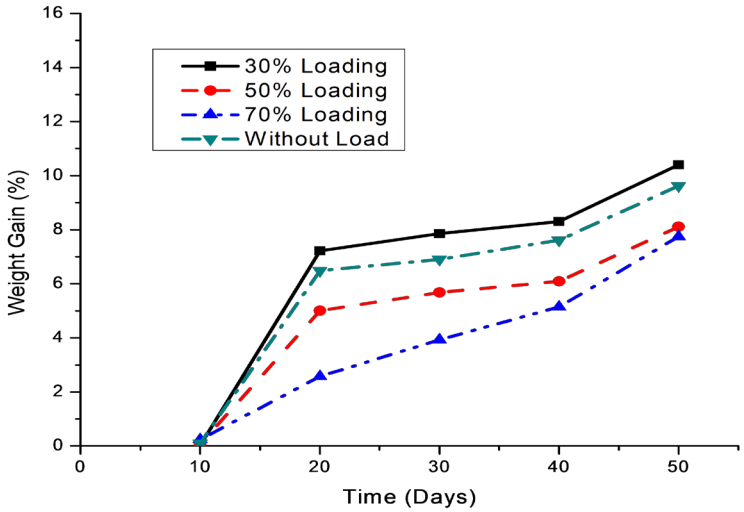

Figure 5 Percentage weight gainin samples of 16 mm core thickness after an interval of 10 days.

It is observed in **Figures 4** and **5** that the percentage weight gain increases with respect to time indicating that more moisture absorbed as the number of days increased in almost all the samples with few exceptions. It is observed that in both the core thicknesses up to 10 days percentage weight gain is not very high but within 10 to 20 days the percentage weight gain was higher.

One of the reasons for the weight gain may be absorption. Absorption occurs through capillary uptake through voids, micro cracks and interface gaps, resulting in the filling of free space with water and increasing its weight. The other could be adsorption, because the temperature of water was 45 °C due to which as time passes swelling in epoxy takes place because of heat and with time the epoxy pores will loosen, giving way to moisture.

Apparent diffusivity

Diffusivity depends upon the mass flow rate of moisture in samples with respect to time. To better understand the results 1 sample of each core thickness and each loading was taken and kept into water at 45 °C and the response of weight gain and diffusivity of each sample in every 3 alternative days was observed. **Tables 3** and **4** show the change in diffusivity.

Table 3 Change in diffusivity of 8 mm core thickness samples with respect to time.

Time/Preload	Diffusivity (mm^2/s)			
	30 %	**50 %**	**70 %**	**Without load**
3 days	0.479	0.425	0.489	0.476
6 days	0.240	0.212	0.245	0.238
10 days	0.144	0.147	0.147	0.143
12 days	0.120	0.106	0.123	0.119
20 days	0.060	0.067	0.076	0.066
30 days	0.039	0.040	0.042	0.040
40 days	0.031	0.033	0.040	0.041
50 days	0.026	0.022	0.020	0.022

Table 4 Change in diffusivity of 16 mm core thickness samples with respect to time.

Time/Preload	Diffusivity (mm^2/s)			
	30 %	**50 %**	**70 %**	**Without load**
3 days	1.253	1.892	1.748	1.477
6 days	0.627	0.595	0.587	0.739
10 days	0.376	0.357	0.352	0.424
12 days	0.314	0.298	0.294	0.370
20 days	0.194	0.195	0.120	0.180
30 days	0.127	0.128	0.109	0.127
40 days	0.084	0.086	0.095	0.095
50 days	0.063	0.061	0.065	0.048

Apparent diffusivity D can be determined as [12];

$$D = \pi \left(\frac{h}{4M_m} \right)^2 \left(\frac{M_2 - M_1}{\sqrt{t_2} - \sqrt{t_1}} \right)^2 \left(1 + \frac{h}{L_e} + \frac{h}{w} \right)^{-2} \quad (2)$$

where

h thickness of the specimen
L_e length of the specimen i.e. 300 mm
w width of the specimen i.e. 40 mm
M_m percentage weight gain
M_1 moisture content after time t_1
M_2 moisture content after time t_2

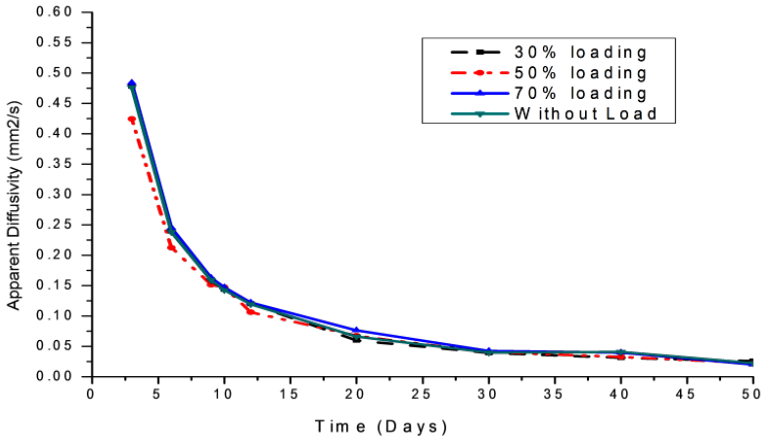

Figure 6 Change in apparent diffusivity in 8 mm core sample w.r.t. time.

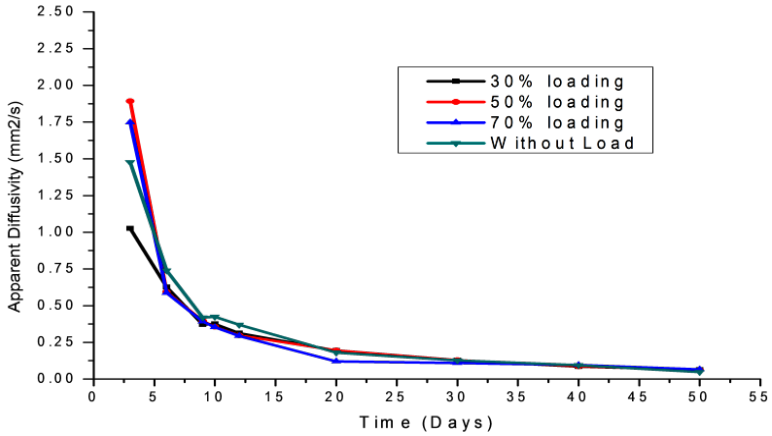

Figure 7 Change in apparent diffusivity in 16 mm core sample w.r.t. time.

Figures 6 and **7** show the trend of change in diffusivity with respect to time. Graphs shows that diffusivity is decreasing with respect to an increase in time in both the core thickness samples and it is almost constant after 30 days. The decrement in diffusity decreases as time passes. It is relatively high during 3 to 6 days. It is also observed that diffusivity of 16 mm core thickness samples are more than 8 mm core thickness samples. The reason for the decrease in diffusivity is due to the increase in percent weight gain and time interval as both percent weight gain and time interval are inversely proportional to diffusivity.

Conclusions

The percentage weight gain showed an increasing trend with time as expected in both core thickness specimens. The percentage weight gain in 16 mm core thicknesses specimen was slightly higher than the 8 mm core thickness specimen. The percentage weight gain in the GFRP sandwich structure subjected to 30 % of ultimate flexure load specimen was higher as compared to the specimen subjected to 50 and 70 % of ultimate flexure load in both core thicknesses.

Apparent moisture diffusivity decreased with time for both core thicknesses, 8 and 16 mm. The slope of change in moisture diffusivity was almost constant after 30 days in both specimens. The decrease in moisture diffusivity was relatively high during 3 to 6 days. For each specimen subjected to flexure pre-load apparent moisture diffusivity of 16 mm core thickness specimen was larger compared to 8 mm core thickness specimen.

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