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Influence of hygrothermal environment on thermal and mechanical properties of carbon fiber/fiberglass hybrid composites

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ABSTRACT

The absorption and diffusion of water in a carbon fiber/glass fiber hybrid composite was investigated. Water-sorption experiments, mechanical property tests and dynamic mechanical analysis (DMA) were performed after immersion in water at different temperatures for up to 32 weeks. The moisture uptake mechanism exhibited by the hybrid fiber system was determined to be more complex than the single fiber type. Weight-change profiles for the composites fitted the theoretical Fickian diffusion curve during the initial immersion time, but diverged substantially as time progressed. The shear properties and the glass transition temperature (T_g) were sensitive to the effects of hygrothermal environment, and values for both decreased with increasing water uptake. Microscopic inspection of water-soaked samples showed no cracking when the absorption was less than saturation. The thermal and mechanical properties were mostly retained (after drying), provided the moisture absorption did not exceed the saturation point.

1. Introduction

In recent years, the advent of commercial-grade carbon fiber and low-cost manufacturing processes has led to new applications for composite materials in industrial sectors outside of aerospace and recreational products. One example of an emerging non-aerospace application is the composite reinforcement of high-voltage overhead conductors, which may eventually replace conventional steel-reinforced conductors and have a major impact in the power industry [1,2].

The effects of environmental exposure of fiber-reinforced polymer composites (FRPC) and the long-term retention of properties are significant concerns for such applications, where the service life can span several decades and little or no maintenance is expected. To design for such service life requires the ability to forecast changes in material properties as a function of environmental exposure, including bulk properties and the integrity of fiber–matrix interfaces. For overhead conductors, environmental attack results primarily from exposure to temperature, moisture, radiation, aggressive chemicals and combinations of these factors with mechanical loads. These factors can (and generally do) affect the mechanical and physical properties of composites in adverse ways, as described in multiple studies [3–8].

Moisture in any form is unfriendly for polymer composites, and often causes swelling and degradation. Matrix and/or interface degradation resulting from moisture absorption is a concern in most composite applications subject to normal atmospheric moisture, which can range from precipitation to mild humidity. Complete immersion in water constitutes the most severe environment, while humid air generally results in lower maximum moisture content [9–11].

Long-term exposure at high temperatures is generally a secondary concern for FRPCs, provided the temperature does not approach the glass transition temperature of the matrix. Liao et al. reported that moisture absorption induced larger strains than high temperature exposure for unidirectional polymer composites, primarily because the coefficient of moisture expansion was greater than the coefficient of thermal expansion [12]. However, higher temperatures accelerate diffusion rates of moisture and generally accelerate aging. Various aspects of moisture-induced behavior and the dependence on such factors have been studied, and both Fickian and non-Fickian diffusion behavior have been reported [5–8,11,13–17].

In this paper, we report the effects of moisture absorption on a unidirectional hybrid composite material developed to support overhead conductor lines [1,2,18]. The hygrothermal effect on the thermal and short beam shear properties was investigated and analyzed. Moisture content, short beam shear strength and glass transition temperature are compared and correlated.

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2. Experimental procedure

2.1. Materials

The hybrid fiber composite used in this study was a unidirectional carbon fiber (CF)/glass fiber (GF) reinforced composite rod, 9.53 mm in diameter, as shown in Fig. 1. The composite rod, which was designed for supporting overhead conductor lines, was manufactured by pultrusion using a propriety epoxy formulation and an anhydride curing agent. The outer shell of the composite rod was reinforced with fiberglass while the internal core was reinforced with carbon fiber. The diameter of CF core was ~7 mm, and the total fiber volume fraction was ~67%. In addition, control samples comprised of all-CF and all-GF composite 6.3 mm rods were produced as the control group to compare diffusion coefficients and behavior.

2.2. Conditioning

Samples were cut to a length of 66.5 mm using a diamond saw, and silicone sealant was applied to the specimen ends to prevent moisture penetration on the cut ends. Prior to water immersion, all specimens were dried in a 100 °C oven for 2 days to remove retained moisture. To assess dryness, a few samples were dried for 8 days at 100 °C, producing a slight additional weight loss that was 3% greater than the weight loss after the standard drying time of 2 days. All samples were then weighed using an analytical balance (ACCULAB LA-60) with 0.01 mg accuracy. The specimens were then placed in large Pyrex dished containing de-ionized water at 40 °, 60 ° and 90 °C, separated by wire mesh to avoid specimen contact. Samples were removed from the baths at predetermined times up to 32 weeks. All samples were subsequently weighed to determine weight change. The weight gain was calculated according to

$$\frac{W_w - W_o}{W_o} * 100\% \tag{1}$$

where W_w is the wet weight and W_o is the dry weight.

After weighing, the specimens were divided into two groups of three samples each. The first group was not dried, and the short beam shear (SBS) strength and T_g was determined in the "wet" state. The second group of samples was dried in a 100 °C oven for 2 days to stabilize the weight, and then the same measurements were performed. Drying the second set of samples was performed to determine if any decrease in property values was reversible by removing the absorbed moisture.

2.3. Short beam shear, thermal properties and visual determination

The influence of the hygrothermal environment on the mechanical and thermal properties was studied. SBS strength testing was measured in accordance with ASTM D4475-02 in a commercial instrument (INSTRON 5567), using a span length 6 times the diameter and a crosshead displacement rate of 1.3 mm/min. Dynamic mechanical analysis (DMA) was performed to determine the shift of T_g. A dual cantilever beam clamp was employed using a commercial instrument (TA Instruments DMA2980). Rectangular samples (60 × 9.5 × 1.6 mm) sectioned from the CF core of the rod were measured and the T_g was determined from the peak in the loss modulus curve. Transverse sections were cut and polished using conventional polishing techniques and then examined microscopically to detect evidence of cracking with different exposure times. In addition, dye penetrate was used to detect cracks in the composite samples.

3. Results

3.1. Moisture absorption

The moisture absorption behavior is shown in Fig. 2, where the percent weight gain is plotted as a function of the square root of the immersion time ($s^{1/2}$) for different temperatures. Each point represents the average of measurements on six specimens, and the error bar is the standard deviation value. The weight gain values for the 40, 60 and 90 °C baths after 5300 h (32 weeks) were 0.53 ± 0.03%, 0.90 ± 0.04% and 11.74 ± 1.22% respectively. The solid lines are the theoretical Fickian diffusion curves obtained by fitting the moisture absorption, M_t, equation [19]:

$$M_t = \left[1 - \sum_{n=1}^{\infty} \frac{4}{a^2\alpha_n^2} \exp(-D\alpha_n^2 t)\right] M_\infty \tag{2}$$

where M_∞ is the saturation level of water absorption, D is the diffusion coefficient, a is the radius and α_n is the nth root of the zero order Bessel function. The Bessel function appears in this equation because of the cylindrical geometry of the samples. The saturation

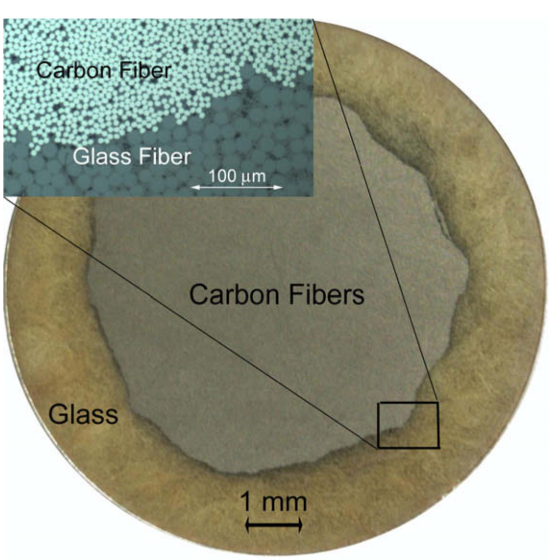

Fig. 1. Cross-section of the pultruded composite core, showing the carbon composite in the center and the glass composite shell around it.

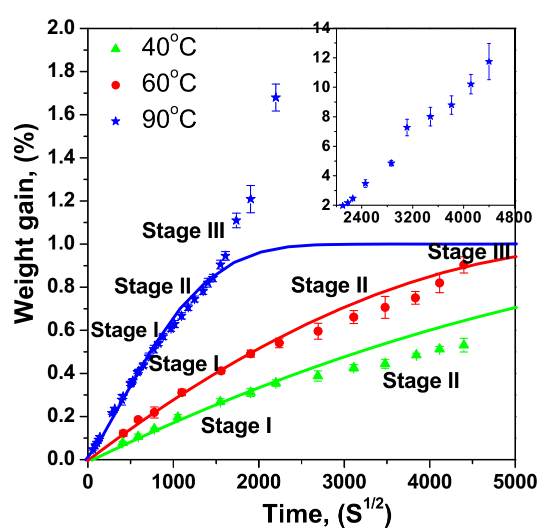

Fig. 2. Weight gain versus the square root of time ($s^{1/2}$) for composites immersed in 40 °C, 60 °C and 90 °C water.