Composites: Part A 43 (2012) 158–164

Contents lists available at SciVerse ScienceDirect

Composites: Part A

journal homepage: www.elsevier.com/locate/compositesa

Moisture absorption of unidirectional hybrid composites

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ARTICLE INFO

Article history:
Received 8 June 2011
Received in revised form 5 October 2011
Accepted 7 October 2011
Available online 14 October 2011

Keywords:
A. Hybrid
A. Polymer-matrix composites
B. Environmental degradation

ABSTRACT

Unidirectional hybrid composite rods were conditioned in humid air to investigate the sorption kinetics and the effects of moisture on mechanical and physical properties. Sorption curves were obtained for both hybrid and non-hybrid composite rods to determine characteristic parameters, including the diffusion coefficient (D) and the maximum moisture uptake (M_∞). The moisture uptake for the hybrid composites generally exhibited Fickian behavior (no hybridization effects), behaving much like non-hybrid composites. A two-dimensional diffusion model was employed to calculate moisture diffusivities in the longitudinal direction. Interfaces and thermally-induced residual stresses affected the moisture diffusion. In addition, the effect of hygrothermal aging on glass transition temperature (T_g), short beam shear strength (SBS), and tensile strength was determined for hygrothermal exposure at 60 °C and 85% relative humidity (RH). Property retention and reversibility of property degradation were also measured. Microscopic inspection revealed no evidence of damage.

1. Introduction

New applications of fiber-reinforced polymer composites (FRPCs) are arising in non-traditional sectors of industry, such as civil infrastructure, automotive, and power distribution. For example, composites are being used in place of steel to support high-voltage overhead conductors. In this application, conductive strands of aluminum are wrapped around a solid composite rod comprised of unidirectional carbon and glass fibers in an epoxy matrix [1]. Composite-core conductors such as these are expected to eventually replace conventional steel-reinforced conductors because of the reduced sag at high temperatures, lower weight, higher ampacity, and reduced line losses [2,3].

Resistance to environmental attack and the long-term retention of properties are major issues that could potentially prevent the widespread acceptance of composite conductors. Conductors during service are typically exposed to moisture and temperatures that eventually can degrade the mechanical properties and lead to premature failure [4,5]. Therefore, understanding the kinetics and mechanisms of degradation during hygrothermal exposure is essential to establish safe limits on service conditions, necessary inspection/replacement frequency, and for design of appropriate protective measures.

Hygrothermal effects on composite properties have been reported for carbon-fiber (CF) and glass-fiber (GF)-epoxy composites exposed to humid air or submerged in hot water [4,6,7]. The moisture uptake for these materials indicated Fickian diffusion behavior in some cases, while in others, non-Fickian behavior was reported [8–12]. While these reports documented the effects of hygrothermal exposure on CF and GF composites, few investigations have focused on the effects of such exposure on hybrid or unidirectional composites [5,13–15].

The purpose of this work was to evaluate the moisture absorption behavior and associated mechanical degradation of unidirectional hybrid composites designed to support overhead conductors. The mechanism of moisture behavior of the hybrid composites was also compared with single-fiber reinforced (non-hybrid) composites, and the radial and longitudinal diffusivities were calculated using the Fickian law. The mechanical and physical properties were measured after different exposure times to evaluate property retention, and samples were dehydrated to determine the extent to which properties could be recovered.

2. Experimental procedure

2.1. Materials

Fig. 1 shows the cross-section of the unidirectional hybrid composite rod used in this study. The rod was 7.75 mm in diameter, and consisted of an inner core of carbon fiber (CF), an outer shell of glass fiber (GF), and an anhydride-cured epoxy (proprietary formulation). The hybrid composite rods (H) were manufactured via pultrusion (Composite Technology Corporation, Irvine, CA) yielding an overall fiber volume fraction of ~67%.

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doi:10.1016/j.compositesa.2011.10.003

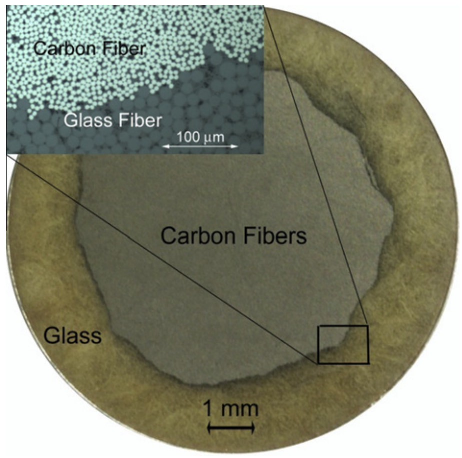

Fig. 1. Cross-section of unidirectional CF/GF hybrid composite rod, showing the CF core region, surrounded by the GF shell [7]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.2. Conditioning

The specimens for the water sorption study were cut to lengths of 48 mm and divided into two groups, end-capped and uncapped. Specimens in the first group were capped on both ends using a silicone sealant to restrict the moisture sorption to the radial direction (assuming uniform diffusion in the radial direction). Note that when conductors are attached to lattice towers in service, the composite ends are placed in aluminum fixtures (dead-ends and connectors). Specimens in the second group were not capped, permitting water sorption in the *z*- and *r*-directions simultaneously.

Fig. 2 shows the weight loss of specimens exposed to air at 60 °C and 100 °C as a function of exposure time, illustrating the dryness of specimens prior to hygrothermal exposure. The weight loss was nearly 0.11% for the first 2 days of exposure, which was attributed primarily to removal of moisture and low-molecular-weight species. An additional 14 days of drying caused an additional 0.01% weight loss, which was attributed to matrix degradation (mainly a dehydration reaction) and removal of sizing. The weight loss within the first 2 days of exposure at 60 °C was less than the loss at 100 °C (see Fig. 2), a result of the lower activation energy for moisture diffusion and low-molecular-weight species. Thus, 2 days of drying prior to hygrothermal exposure was sufficient to remove nearly all of the absorbed moisture resulting from exposure, and this drying period was adopted to prevent further thermal degradation. Note that no thermal degradation occurred after 2 days of exposure at 60 °C (identical to the moisture exposure temperature).

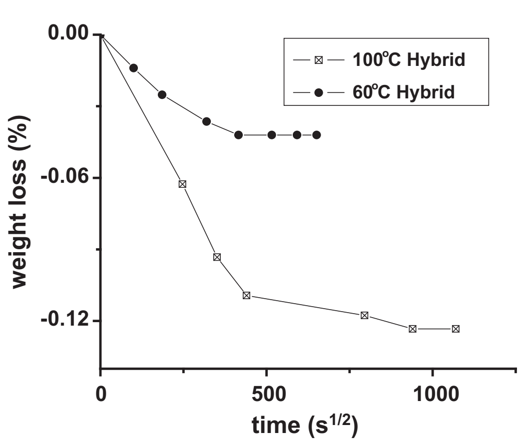

Fig. 2. Weight change of the specimens as the function of exposure time at 100 °C and 60 °C.

Specimens for water sorption measurements and for mechanical and thermal testing were conditioned in an environmental chamber set to conditions of 60 °C and 85% relative humidity (TPS T30RC-2 and Hotpack 435304). Specimens were periodically removed from the environmental chamber to measure weight change using an analytical balance with 0.01 mg accuracy (ACCU-LAB LA-60). The specimens were also removed periodically to conduct thermal and mechanical tests in the *wet* and *dry* states (achieved by drying for 3 days at 100 °C). Dried specimens were evaluated to determine the extent of reversibility in properties after moisture absorption experiments. Prior to weighing, all specimens were surface-dried to remove residual surface water. The weight change was calculated according to:

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

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

2.3. Short beam shear strength, tensile strength, thermal stability and inspection

Short beam shear strength (SBS) and tensile strength measurements were performed to determine the effects of hygrothermal exposure. For SBS measurements, specimens were cut to 66.5 mm, while tensile samples were cutto 106.7 mm. SBS was measured at room temperature in accordance with ASTM D4475-02 using a load frame (INSTRON 5567) and a bend fixture with a span length six times the diameter and a crosshead displacement rate of 1.3 mm/min. Tensile strength was measured using a universal testing machine (INSTRON 5585) at room temperature in accordance to ASTM D3916-02. The initial values of SBS and tensile strengths were 46 MPa and 2280 MPa.

The change in glass transition temperature (T_g) with exposure time was determined by dynamic mechanical analysis (DMA, TA Instruments DMA2980) with a dual cantilever beam clamp. Sample beams 60 × 9.5 × 1.6 mm were cut from the CF core of the rod. A load frequency of 1 Hz was imposed over a temperature range of 25–250 °C, and T_g was determined from the peak of loss modulus curve.

Transverse and longitudinal sections of the exposed samples were cut and polished using a broad-beam ion polisher (JEOL SM-09010). Ion polishing (∼5.2 kV and ∼110 mA) resulted in sections free of relief, preserving the exposed layer. Light microscopy (Olympus Vanox) and scanning electron microscopy (SEM; JSM 7001F) were used to examine the polished sections.

2.4. Calculation of 1D and 2D moisture diffusion

Capping specimens ensured that moisture diffused only in the radial direction. The amount of moisture diffusing in time *t*, M_t, can be expressed as follows [16]:

$$\frac{M_t}{M_\infty} = 1 - \sum_{n=1}^{\infty} \frac{4}{R^2 \alpha_n^2} \exp(-\alpha_n^2 D t) \tag{2}$$

where M_∞ is the saturation level of water absorption, D_r is the radial diffusion coefficient, *R* is the radius, and α_n is the n_{th} root of the zero-order Bessel function. Note that the effects of CF core/GF shell interface on the moisture diffusion are assumed to be negligible, and diffusion along fiber–matrix interfaces is neglected. In addition, the D_r is the average diffusivity over locations, calculated from the best fit of Eq. (2) to experimental data.

Uncapped rods allow for moisture diffusion both axially (through the rod ends) and radially during humidity exposure