

Effect of Water Absorption on Tensile and Fatigue Behaviors of Two Short Glass Fiber Reinforced Thermoplastics

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ABSTRACT

An experimental study was conducted to evaluate the effect of water absorption on tensile and fatigue behaviors of an impact-modified short glass fiber polyamide-6 and a short glass fiber polybutylene terephthalate. Specimens were prepared in the longitudinal and transverse directions with respect to the injection mold flow direction and immersed in water. Kinetics of water absorption was studied and found to follow the Fick's law. Tensile tests were performed at room temperature with specimens in the longitudinal and transverse directions and with various degrees of water absorption. Mathematical relations were developed to represent tensile properties as a function of water content. Load-controlled tension-tension fatigue tests were conducted in both longitudinal and transverse directions and correlations between tensile and fatigue strengths were obtained. Specimen fracture surfaces were also microscopically studied and mechanisms of tensile and fatigue failures were identified.

CITATION: Mortazavian, S., Fatemi, A., and Khosrovaneh, A., "Effect of Water Absorption on Tensile and Fatigue Behaviors of Two Short Glass Fiber Reinforced Thermoplastics," *SAE Int. J. Mater. Manf.* 8(2):2015, doi:10.4271/2015-01-0546.

INTRODUCTION

Application of short fiber reinforced polymers (SFRPs) is increasingly growing, particularly in the automotive industry due to their high production rate and relatively low cost. Components made of SFRPs are typically exposed to environmental effects such as water or moisture in actual service applications.

Nearly all polymers can absorb water and the amount of absorbed water depends on the polymer composition and hydrophobicity. In fiber composites, microvoids and cracks exist near the interface between fiber and matrix. Therefore, because of capillary, water molecules can enter the fiber-matrix interface through these interspaces and simultaneously diffuse into matrix. The capillary is a process in which the water molecules with a low surface energy roll out on other materials with a higher surface energy [1].

Polymer tendency to moisture absorption decreases with increasing fiber content which is due to reduction of the hygroscopic phase, matrix, as fiber content increases. However, the type of fiber can change the soakage of water through occurrence of capillarity and influence the water content and absorption rate. The penetration of moisture in polymer composite along the fiber is 100-400 faster than

through resin [2]. Presence of coupling agents can reduce the water diffusion by constraining the occurrence of capillary in the interphase between fiber and matrix.

Presence of voids which results from either air entrapment in the manufacturing process or vaporized components at high temperature cure cycle of composites can also increase the diffusivity of moisture into the composites [3]. The water absorption process in polymer-based materials is typically based on the Fick's law. However, the behavior may depart from the classical formulation of Fick in polymer composites [4] and Langmuir model can be used to simulate the non-Fickian diffusion behavior [5].

The absorption of water can cause swelling of the polymer and, therefore, at the interphase between fibers and matrix, tensile stress is initiated due to rigidity of fibers restraining swelling of the polymer. Plasticization of the polymer through displacement of polymer molecules and weakening of the interphase between fiber and matrix are other consequences of water absorption [6, 7]. Fiber-matrix debonding is the failure mechanism in the permanent performance loss, while the plasticization effect of water is reversible after desorption of water [2].

In addition to the silica as the main component, most common glass fibers contain other ingredients to change their properties. The environment can chemically affect the glass fibers through their nonsilica components [2]. A silane coupling agent protects the fiber-matrix interface and provides higher shear stress transferability between fibers and matrix. In coated fiber composites, only at fiber ends the yielding of interface can reduce the transferability of shear stress. Therefore, matrix plasticization can be the main influence of water absorption in composites with silane coupling agents [7].

Mechanical performance of polymer composites under monotonic and cyclic loads is controlled by fiber and matrix types and fiber-matrix interface. A number of studies have investigated effects of different humidity levels on tensile behavior of SFRPs. The number of studies on their cyclic behavior is small compared with the number of studies on tensile behavior [8], although many components are under cyclic loading and susceptible to fatigue failure.

Valentin et al. [9] evaluated effects of water absorption on tensile behavior of short glass fiber reinforced polyamide-6.6. Specimens were exposed to various temperatures including 40, 70, and 90 °C under relative humidity levels consisting of 30, 75, and 100%. Bending tests were performed on specimens with different water concentration levels. For water absorption above 1%, tensile strength and modulus were considerably reduced.

Bergeret et al. [10] studied the hygrothermal behavior of three short glass fiber reinforced thermoplastics including polyamide-6.6 (PA66), polybutylene terephthalate (PBT), and polyethylene terephthalate (PET). The maximum water absorption for PA66 at 135 °C and for PET and PBT at 120 °C composites was obtained at 9%, 3% and 1%, respectively. The maximum water absorption and the water absorption rate increased with aging temperature due to easier diffusivity of water at higher temperatures. Reduction of tensile strength at mentioned aging temperatures was 50%, 85%, and 60% for PA6, PET, and PBT, respectively.

Lyons [11] evaluated tensile behavior of short glass fiber polyamide-4.6 and -6.6 and short glass fiber reinforced polyphthalamide composites. Specimens were aged between 50 to 3600 hours at 23, 100, and 150 °C in air, and then tested at the same temperature as thermal aging. At 23 °C and 100 °C, isothermal aging showed little effect on elastic modulus, tensile strength, and percent elongation of both materials, while at 150 °C due to chemical aging (oxidation) of the polymer, tensile strength and percent elongation decreased as aging time increased.

Bastioli et al. [12] studied the water absorption effect on polybutylene terephthalate (PBT) and polyethylene terephthalate (PET) thermoplastics. The water absorption increased as aging temperature increased, due to modification of crystalline-amorphous interface during absorption process. At the same temperature, PET absorbed more water resulting from lower crystallinity of PET compared to PBT. At temperatures above the glass transition temperature (T_g), a plateau of water absorption followed by an increase at sufficiently high aging time. This increase was attributed to presence of hydrophilic carboxyl groups resulting from chain breakage. In graphs of water absorption versus time for PET, a concavity was observed

before reaching a plateau. This concavity was resulted from the formation of crystallites acting as impenetrable agents. An increase of toughness under short time aging at 87 °C was observed and attributed to synergic effects of water plasticization and stress relaxation at high temperatures.

Carrascal et al. [13] studied the absorption of moisture at various temperatures and relative humidity levels in neat and short glass fiber polyamide-6. As temperature increased absorption of moisture occurred faster, but the maximum capacity of water absorption did not change. The maximum water absorption was about 8.5%, 6.4%, and 5.4% for neat polyamide-6 and 25 wt% and 35 wt% short glass fiber polyamide-6, respectively. A parameter was defined to evaluate influences of water absorption on fibers and interfacial bonding. This parameter was defined as the ratio of weight of absorbed water in composite and weight of dried matrix itself. Nearly identical values of this parameter were obtained for composites with different volume fractions, confirming no effect of fiber glass in absorption of water.

Ishak and Berry [14] investigated the hygrothermal aging of short carbon fiber reinforced polyamide-6.6 at temperatures ranging between 25 and 100 °C. At all temperatures the amount of absorbed moisture linearly increased with square root of time and then reached a plateau, with a slight increase in the maximum moisture with increasing the temperature. At equilibrium, the maximum water absorption was about 5.5% by weight. The moisture increased the matrix ductility and reduced the effectiveness of interfacial bonding.

Ishak and Lim [15] studied effect of moisture absorption on tensile properties of short glass fiber reinforced polybutylene terephthalate. The equilibrium moisture increased with decreasing fiber content due to increased volume fraction of hygroscopic phase (i.e. matrix). The equilibrium moisture content for unreinforced PBT and reinforced PBT with 17% fiber volume fraction was 0.85 and 0.7% by weight, respectively. A slight decrease in diffusivity was reported in composites relative to neat polymer, due to distribution of fibers hindering the direct moisture diffusion. Drastic decrease of tensile strength and elastic modulus was reported under the influence of moisture. A more pronounced effect of moisture was observed at 100% relative humidity compared with 81% relative humidity, due to extensive plasticization and hydrolysis of matrix as well as degradation of fiber-matrix interface at 100% relative humidity. Hydrolysis was concluded from the presence of microvoids on the fractured surfaces. Tensile properties of specimens did not fully recover after drying subsequent to exposing in 100% relative humidity, while percentage of recovery was higher for reinforced composites compared with neat polymers. This effect was attributed to hydrolyzing effect of water molecules on polymer matrix in addition to plasticizing, which was less pronounced for composites due to presence of short fibers.

Hassan et al. [16] studied the effect of moisture absorption on tensile properties of short glass fiber reinforced polyamide-6.6. Tensile tests were conducted on specimens in dry condition as well as saturated at 50% and 100% relative humidity. Tensile strength and elastic modulus decreased as degree of humidity increased, but the failure strain increased. As polymer composites absorb moisture, a hydrogen bonding between moisture and matrix forms and the interaction

between polymer and fibers become less effective. As a result, matrix cannot transfer the load to a sufficient length of fibers, fiber breakage occurs less, and failure strain increases. Under wet conditions, matrix yielding and interfacial debonding between fiber and matrix was dominant, while in dry condition a brittle matrix fracture was observed with no sign of matrix deformation.

Hoppel [17] investigated axial load-controlled fatigue behavior of short glass fiber reinforced styrene-maleic anhydride. Specimens were immersed in water for 48 hours prior to and throughout the test and fatigue life was much shorter than the dried specimens tested at 25 °C and 50% relative humidity. The effect of moisture on fatigue life was more pronounced for materials with no silane coupling agent. This agent provides a strong bonding between matrix and fillers. Stiffness reduced at a higher rate for wet specimens compared to the dried specimens.

Barbouchi et al. [18] evaluated the effect of moisture on bending fatigue behavior of short glass fiber reinforced polyamide-6.6. Fully-reversed strain-controlled tests were conducted on two sets of samples with 0.2 wt% and 3.3 wt% water contents. About 80 °C reduction of T_g was observed in samples with higher water content, due to the plasticizing effect of water which increases the mobility of polymer chains. For a given strain, the fatigue life was higher for samples with a higher degree of moisture because the induced stress was much lower due to the plasticizing effect of water. In samples with 0.2% water content, a sharp decrease in modulus was observed due to the transition of matrix from glassy state to the rubbery state. However, samples with 3.5% water content were in the rubbery state from the beginning of the test and the decrease of modulus was due to damage initiation.

The aim of this study was to investigate effect of water absorption on tensile and fatigue behaviors of two common short glass fiber reinforced thermoplastics. The kinetics of water absorption is modelled and the maximum capacity of water absorption is evaluated. Tensile tests were conducted on samples with different contents of water and variations of tensile properties with water content are mathematically represented. Fatigue tests were also conducted and correlations between tensile and fatigue strength are suggested. Microstructural examinations were also performed on tensile and fatigue fractured surfaces of specimens. The effect of temperature on tensile behavior of these materials was investigated in another publication [19].

EXPERIMENTAL PROCEDURES

Materials

Materials used in this study are injection molded short glass fiber reinforced polybutylene terephthalate containing 30 wt% short glass fibers (designated as PBT) and impact modified short glass fiber polyamide-6 containing 35 wt% short glass fibers and about 10 wt% rubber (designated as PA6). The mean aspect ratio of glass fibers defined as the ratio of mean fiber length to mean fiber diameter, was measured at 26 [20]. For both materials, the melt temperature was at

220 °C and the glass transition temperature (T_g) was measured at 60 °C in dried as-molded condition from loss tangent peak in dynamic mechanical analysis (DMA) tests.

Experimental Method

The raw material was injection molded to rectangular plaques with dimensions of 3.8 mm × 100 mm × 200 mm. Specimens were machined from middle of plaques in both longitudinal and transverse directions with respect to the direction of injecting mold flow. The specimen geometry used is shown in Figure 1.

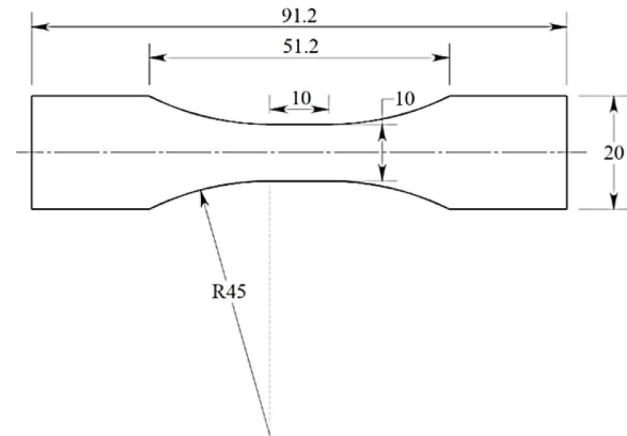


Figure 1. Specimen geometry used for tensile and fatigue tests (dimensions are in mm).

Specimens were preserved in both dry and wet conditions and tested at room temperature and relative humidity of 20-30%. For dry condition, PBT and PA6 specimens were dried for 6 hours at 120 °C and 80 °C, respectively, prior to testing. For wet condition, specimens were immersed in room temperature water between 1 and 140 days, prior to testing. A summary of testing conditions for PA6 is provided in Table 1.

Table 1. Summary of tensile test conditions for PA6.

Specimen Number	Mold Flow Direction	Immersion Time (h)	Drying Time (h)	Percent Water (wt.)
<i>Dry</i>				
1	L	0	6	0
2	L	0	6	0
3	T	0	6	0
4	T	0	6	0
<i>Wet</i>				
5	L	100	0	1.7
6	L	100	0	1.7
7	L	240	0	2.4
8	L	480	0	3.0
9	L	720	0	3.6
10	L	1680	0	5.0
11	L	2160	0	5.2
12	L	2160	6	3.1
13	L	2160	30	1.6
14	L	100	8	0.25
15	L	100	8	0.25
16	T	100	0	1.4
17	T	0	0	1.4