Effect of Repeated Loading on Moisture Absorption of Fiber Reinforced Polymer Composites

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Abstract: Although known for their ease of production and high specific properties, fiber reinforced polymer composites are highly susceptible to environmental conditions such as moisture absorption. While the adverse effects of moisture on composite parts are well documented, effects of repeated loading on moisture absorption of composites are not fully known. This work investigates the effect of repeated loading on moisture absorption of resin transfer molded glass/epoxy composites. Disk-shaped parts (D=152.4 mm) are fabricated using Epon 815C resin and Epi-cure 3282 curing agent. Reinforcement is provided by six layers of randomly oriented planar glass fiber performs with 0.459 kg/m^2 surface density, yielding approximately 32.4% fiber volume fraction. Three point bending tests are performed on samples cut from the molded disks in order to evaluate their short beam shear strength (SBSS). After SBSS is determined, load levels that correspond to 30, 50, 70 and 90% of the SBSS are applied 1, 2, 5 and 10 times, thus imparting various levels of low-cycle fatigue damage. A set of unloaded specimens is kept to characterize the baseline moisture absorption behavior of the composite samples. The fatigue-loaded specimens are subsequently immersed in water at room temperature. The masses of specimen are measured at periodic intervals to quantify the amount of moisture absorbed. Maximum moisture absorption is found to increase almost linearly with the stress level applied to the different composite parts. Maximum moisture absorption is also found to increase with the increasing number of loading cycles. In addition, stiffness reduction after loading and after moisture absorption is measured. Stiffness reduction, initially correlated to the number of loadings, is observed to substantially increase after moisture absorption for all samples and reach a plateau around 12.85%.

Introduction

In recent years, there has been a rapid integration of fiber-reinforced composite materials into key technological areas, such as transportation and infrastructure, demanding lower weight/strength ratios, longer lifetimes and lower cost. In aerospace and automotive industries for instance, switching from light weight conventional materials to fiber reinforced composites even in primary structural components has been the trend for more than a decade. Utilization of mass production capabilities for composites is likely to increase the areas of application of such materials in all industries.

Resin transfer molding (RTM) is an attractive fabrication method for fiber reinforced composites, due to its short cycle times, low pressure requirement, and significantly lower manufacturing costs compared to other composite manufacturing techniques. The process is carried out by impregnating the fiber reinforcements that are placed in a closed mold with a resin-curing agent mixture. The exothermic curing reaction between the resin and curing agent in the mold causes the fluid to harden, thus forming the final part. The curing process may take minutes to days depending on the resin-curing agent chemistry, the part dimensions and the fiber volume fraction. After the curing process is complete, the final part is removed from the mold. Generally, RTM parts do not require further finishing operations since, in most cases, a release agent is sprayed on the mold surfaces prior to fiber placement to make part removal easier and to prevent damages to both the part and the mold surface during removal [1-2].

Properties of final parts are determined by the type of resin and fiber reinforcement used as well as the flow dynamics during the impregnation process [1-4]. The strength of the final part is dominated by the type and amount of fiber reinforcements placed in the mold prior to impregnation. Unlike more traditional autoclave molding, resin transfer molding provides further control on the final fiber volume fraction, since the amount of fiber and resin present in the mold during impregnation does not change.

Flow dynamics during the impregnation process also affect the mechanical properties of the final part. During mold filling, ill defined fluid and flow parameters, mold geometry or preform permeability can induce the formation of voids and dry spots. These voids are long known to affect the mechanical performance [5-7] and resistance to environmental effects [8-9], thus shortening the service life of composite products. In an earlier review article, Judd and Wright [5] summarized adverse effects of voidage on mechanical properties of composites for a variety of resins, fibers, and fiber surface treatments. In more recent studies, voidage effects on mechanical properties of fiber reinforced composites were investigated. For example, Goodwin et al. [6] reported a 7% reduction in interlaminar shear strength per 1% increase in voidage up to 10% for an RTM composite. Our research group also reported that doubling the void content from 0.35 to 0.72% results in a 15% decrease in ultimate tensile strength and 14% decrease in stiffness for resin transfer molded composites reinforced with 21% E-glass preforms [7].

In addition to adverse effects on mechanical performance, void content is known to affect both the rate and equilibrium level of composites' moisture absorption. Even minor increases in void fraction are reported to increase the moisture diffusion rate by a factor of 6 [8,9]. In turn, moisture presence considerably decreases the fabricated composites' mechanical performance as presented in our earlier studies [10-12]. A number of investigations were conducted by our research group on reducing voidage in RTM composites, and applying a post fill pressure after the mold cavity is filled was found to lower void occurrence in molded parts [13-15].

Notwithstanding ease of production and other favorable properties, fiber reinforced composites are highly vulnerable to environmental conditions. Among these, the diffusion of moisture into the composite material is known to degrade the mechanical properties. In polymeric composites, the moisture is diffused by two basic mechanisms: either by getting into the existing voids and fiber-matrix interphase or by making bonds with the polymer chain. A number of factors affecting these mechanisms lead to variations in moisture absorption behavior of the composites. Fiber volume fraction, temperature and relative humidity of the environment, as well as the void content, hydrostatic pressure and the stress state of the composite are identified as the important factors influencing moisture absorption.

In the absence of voids and microcracks, moisture is primarily absorbed by the resin. Therefore, both diffusivity and maximum moisture absorption depend strongly on fiber content [16-20]. For example, Choi et al. [16] investigated several aspects of moisture absorption characteristics of carbon/epoxy laminates. Composite samples with four different matrix volume fractions ranging from 29 to 45% were subjected to moisture absorption at 70°C and 95% relative humidity. The diffusivity increased linearly from $0.3x10^{-9}$ to $1.3x10^{-9} cm^2/s$ with increasing matrix volume fraction from 29 to 45%. In a similar study by Mohd Ishak and Lim [17], a change of maximum moisture absorption and diffusivity in distilled water at 100°C with fiber volume fraction is observed. The diffusivity and maximum moisture absorption reduced by 39.7 and 15.3%, respectively as the fiber volume fraction increased from 0 to 17%.

Since temperature and relative humidity of the environment affect the kinetic energy of the water molecules and the concentration at the boundaries, they have influence on the absorption characteristics of the composite materials [16-20]. In a study comparing the moisture absorption behavior of the chemically treated and untreated aramid/epoxy composites, Doxsee et al. [18] reported the effects of temperature and relative humidity on the diffusivity and maximum moisture absorption. Samples are conditioned at combinations of 50 and 76°C and 70, 85 and 95% relative humidity. At 76°C, changing the relative humidity from 70 to 95% resulted in 100 and 29.4% increase in diffusivity and maximum moisture absorption, respectively. The effect of temperature on the equilibrium water uptake of autoclave molded carbon/epoxy composites is studied by Suh et al. [19]. Samples having 55% fiber volume fraction are immersed into distilled water and kept at 5 different temperatures ranging from 35 to 95°C in constant temperature water baths. The equilibrium water absorption increased by 32% as the temperature of the environment increased in the range investigated.

Another parameter changing the water absorption behavior is the overall void content of the composite [16,20]. Hoppel et al. [20] worked with graphite fiber reinforced epoxy composites with various void contents. They concluded that the diffusivity increases significantly even with a small increase in void content. Tucker and co-workers [21-22] investigated the effects of hydrostatic pressure on the moisture absorption of vinyl ester/graphite composites. With the aid of a pressure chamber, the samples are pressurized to a level corresponding to a depth of 2000 feet (609.6 meters) of seawater. Although the diffusivities remained constant, samples conditioned under pressure had approximately 50% higher equilibrium moisture content. Choi et al. [16] also studied the effect of stress on the moisture absorption behavior of composite laminates. Composite samples are subjected to a bending load during sorption process. Releasing the load after reaching moisture equilibrium restarted the sorption and samples reached the same equilibrium with the unstressed ones.

In a number of studies, degradation of the mechanical performance of fiber reinforced composites due to moisture absorption is observed [16-19,21-26]. The quality of fiber matrix interphase in a polymeric composite can best be described by the interlaminar shear strength. The accumulation of water at the fiber matrix interphase causes deterioration of the interphase, thus leading to a reduction in the interlaminar shear strength [23-26]. In a study by Akay et al. [23], the reduction in interlaminar shear strength of laminated kevlar/epoxy composites are investigated. Linear decrease in interlaminar shear strength at a rate of 4% per 1% absorbed moisture is observed. In a later study, the degradation of interlaminar shear strength in glass fiber reinforced PEI composites is demonstrated by Viña et al. [24]. Samples are conditioned in distilled water at room temperature before testing. Unlike kevlar/epoxy laminates [23], the interlaminar shear strength dropped by approximately 28% at 70% of the maximum moisture absorption and remained almost constant afterwards.

Our research group investigated effects of several parameters on moisture absorption behavior of E-glass/epoxy RTM composites. Moisture absorption characteristics and its effects on the mechanical performance of resin transfer molded glass/epoxy composites are studied. The moisture diffusion process in these composites is shown to follow Fick's Law [10-12].

Mechanical property deterioration was investigated by using tensile and three point bending tests. Results of both tests reveal significant reductions with moisture content. For example, presence of 3.4% moisture was observed to cause 46.2% reduction in ultimate tensile strength and 38.5% drop in short beam shear strength of composite samples with 14% fiber content conditioned at 100°C [10]. While at 45°C, moisture intake is found to decrease almost linearly with increasing fiber volume fraction varying between 0 and 24.5%. Interlaminar shear strength reduction is found to be much higher for higher fiber volume fractions. The reason for having elevated reductions at higher fiber contents was attributed to the reduction in bonding strength at the fiber matrix interphase [11-12].

Interlaminar shear strength is not the only mechanical property affected by moisture absorption. Numerous studies reported the decrease of the flexural stiffness [10-12,21-25], the energy absorption performance [29-32] and the glass transition temperature [10-12,16,23,26] of the polymeric composites.

Moisture absorption in polymeric composites is normally modeled using Fick's Law, which leads to a linear, second order partial differential equation describing the mass diffusion. This equation can be solved in different domains yielding the moisture distribution throughout the part as given by Crank [33]. The transient moisture distribution in a slab of finite thickness, shown by Shen and Springer [34], is among the earlier application of Fick's diffusion law to fiber reinforced composites. The slab considered in Ref. [12] is assumed to be infinitely long in two directions so that moisture diffusion occurs in through-the-thickness direction only. The solution is also accompanied by the edge effect corrections for the prediction of diffusivity. Upadhyay and Mishra [35] suggested an empirical modification to the theoretical solution for cases where the experimental data and the theoretical solution do not agree due to non-Fickian effects. Additional parameters are introduced to the solution by considering: (a) the influence of swelling of the matrix; (b) free phase assumption of the model, and (c) the fact that boundary moisture concentration is not achieved instantaneously. However, model verification with experimental data is not presented in their study.

While the effects of moisture absorption on mechanical performance of fiber reinforced composites have been well scrutinized, knowledge of the effect of loading on moisture absorption remains limited. In the literature, parts that undergo moisture absorption and testing are in most cases fabricated for that purpose and did not undergo any loadings. However, during its life cycle, a fiber reinforced composite part will endure various series of cycles: uneven loading cycles, moisture absorption desorption cycles as well as temperature changes, or even at the same time. Since fiber reinforced composites are prone to moisture absorption during their whole life cycle, we need to address moisture absorption behavior of a mid-life cycle composite part. To the best of the authors' knowledge, no such study has been undertaken before. Hence, we study here the effect of repeated loading on moisture absorption in such materials.

Experimental Studies

Molding procedure

The composite disks used in this study are fabricated using a custom-made molding setup, depicted in Fig. 1. This experimental setup comprises a hydraulic press; two reservoirs for resin and curing agent; a static mixer; and a disk-shaped mold cavity. When operated, the 40-ton hydraulic molding press forces the Epon 815C resin and Epi-cure 3282 curing agent, of Shell Chemicals, out of the reservoirs into the mold cavity. The steady motion of the hydraulic press provides a constant volumetric flow rate of $5.8 \times 10^{-6} m^3/s$ for the resin-curing agent mixture. The outflows from the cylinders are merged by a t-connector and passed through an inline static mixer with 32 alternating helical mixing units, which provides thorough mixing of resin and curing agent. The mixture then enters the mold through a 6.4mm diameter inlet gate located at the center of the mold cavity. The mold cavity is formed by placing a 3.2mm thick spacer plate with a 152.4mm diameter circle cut out at its center, between two aluminum mold walls. A set of o-rings on both mold walls prevent leakage and enable application of the post fill packing pressure.

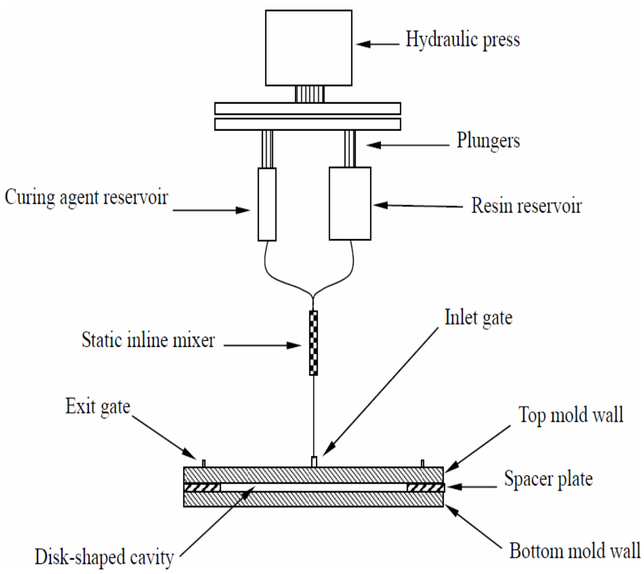

Fig. 1. Experimental molding apparatus used to fabricate fiber reinforced polymer composites.

Resin/curing agent mixture is injected into the mold cavity until the mixture comes out of the four exit gates placed symmetrically on the top mold wall. After filling is completed and exit gates are clamped, the press is operated for an additional second for the application of post fill packing pressure. Application of post fill packing pressure is shown to lower void occurrence [13-15] and hence improve the performance of resin transfer molded parts [7]. Following the application of post-fill packing pressure, the inlet is clamped and the mold assembly is removed for curing. Curing is carried out at room temperature for two days until the disks become rigid enough to be de-molded. Six layers of randomly oriented, chopped-strand, E-glass fiber planar glass fiber performs with 0.459 kg/m2 surface density, are respectively placed in the mold cavity prior to filling. The final parts are three composite disks with approximately 32.4% fiber volume fraction.

Sample Preparation

As depicted in Fig. 2, a total of five 11.43cm long composite pieces are cut from each fabricated disk using a vertical milling machine. An aluminum template is used to hold the disk in place during cutting operation. Pieces are numbered from one to five and are polished using a 300 grit sand paper to clear the edge irregularities due to cutting. A band saw is used to cut each of the five long pieces into three 38.1mm long parts as shown in Fig. 2. Thus, a total of 15 38.1mm-long, 12.7mm-wide samples are obtained per disk. Thicknesses of the samples are measured using a micrometer with 0.001mm precision.

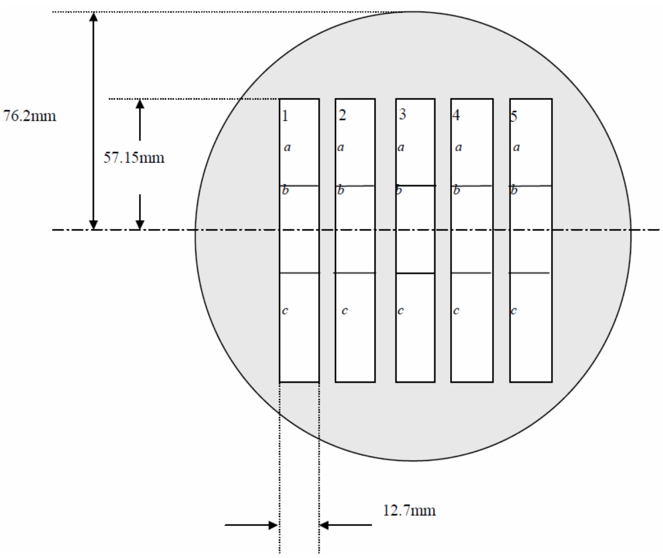

Fig. 2. Spatial position of specimens cut from the fiber reinforced polymer composite disks.

After discarding samples corresponding to disk centers due to the surface defects left by the inlet gate, fourteen usable specimens are obtained from each molded disk. Four samples from each disk are tested mechanically in order to evaluate their short beam shear strength prior to moisture conditioning. The obtained results are also used to set the different loadings for the remaining samples. Sample from one disk, at the dry stage, are utilized to investigate the effect of the maximum loading on moisture absorption, while samples from the second disk are used to examine the effect of repeated loadings on moisture intake.

Short Beam Shear Testing

Three point bending tests are performed on samples cut from the molded disks in order to evaluate their short beam shear strength (SBSS). Short beam shear strength is an effective way of determining the quality of fiber-matrix interphase of a polymeric composite material. The test involves supporting a specimen at two ends and loading it from the center. For this test, a three point bending fixture (MTS series #642) with two adjustable supporting rollers and a loading roller is mounted on the MTS machine. The top loading roller is moved at a constant speed of 1.27 mm/min (0.05 in/min) exerting bending force at the center of the sample. The maximum force measured until failure is determined and short beam shear strength is evaluated according to ASTM D 2344/D2344M-00 standard [36].

After SBSS is determined, various levels of low-cycle fatigue damage are imparted on the prepared composite samples. Loading levels corresponding to 30, 50, 70 and 90% of the SBSS are applied to a first set of samples. Another set undergoes 1, 2, 5 and 10 loading cycles at 30% SBSS. Each three point bending loading is executed at least on two samples. A set of four unloaded specimens is kept to characterize the baseline moisture absorption behavior of the composite samples. At the end; a total of 20 samples are used in moisture conditioning. Afterwards, three point bending tests are again performed on the moisture-conditioned samples in order to evaluate the stiffness reduction.

Moisture Conditioning

The loaded specimens are thereafter immersed in distilled water at room temperature. Moisture absorption experiment is conducted as specified by the ASTM D 5229/D 5229M standard [37]. All samples are dried in a vacuum oven at 65°C for approximately 7 days before any conditioning or testing to ensure complete removal of the initial moisture content of the samples. Moisture uptake is performed in a constant-temperature water bath (Brookfield TC200) at 25°C, as described by the

ASTM D5229/D5229M standard. The temperature of the water bath is constantly monitored with a built in thermocouple, and variation greater than 0.1°C is not observed throughout the absorption period. Manufacturer specified precision of the water bath is ±0.03°C, which is well below the maximum variation allowed by the ASTM standard. Before moisture uptake, the mass of each sample is measured by an electronic balance (Fischer Scientific, Model 2200) with 0.0001g precision. The samples are placed into 20 different plastic bags filled with distilled water and placed into the water bath. Samples are weighed periodically and percent mass gain for each group is calculated. Moisture conditioning is continued until the masses of the samples ceased increasing after nine and a half months.

Results and Discussion

Effect of loading levels on moisture absorption

The methodology adopted by *American Society of Testing and Materials* is the most common way of determining the one dimensional diffusion coefficient in polymer composites. For a three-dimensional rectangular sample, with thickness *h*, width *w*, and length *l*, the total percent mass gain at a given time, *t* can be written as:

$$M(t) = \frac{4M_m}{h}\sqrt{\frac{D_z}{\pi}}\sqrt{t} \tag{1}$$

where $M(t)$ is the percent moisture absorption at time t, M_m is the maximum percent moisture absorption and D_z is the through-the-thickness diffusivity.

Equation (1) depicts a linear mass increase with the square root of time without reaching a final equilibrium level. That is because the solution is obtained for a semi-infinite domain. However, in an actual diffusion process, the matter diffuses into medium from all directions. At the initial stages of moisture absorption, effects of other sides on the absorption are negligible and mass gain can well be described by equation (1). The application of this approach in finding the diffusion coefficient can be achieved by equating the initial slope of the experimentally obtained curve and that of equation (1). Doing as such, one can obtain the closed-form solution for the diffusion coefficient as:

$$D_z = \pi\left(\frac{h}{4M_m}\right)^2\left(\frac{M_2 - M_1}{\sqrt{t_2}-\sqrt{t_1}}\right)^2 \tag{2}$$

In experimental analysis of moisture absorption, percent mass gain is plotted versus square root of time. In this case, second parenthesis in equation (2) is the initial slope of the experimental moisture absorption curve.

The moisture absorption behavior of the samples loaded at different levels is depicted in Fig. 3. A special measuring calendar was made in order to ensure evenly spaced weighing with respect to root square of time as stated by the ASTM standard. The experiments were stopped after the samples weight stabilized, which corresponds to nine and a half months of moisture conditioning.

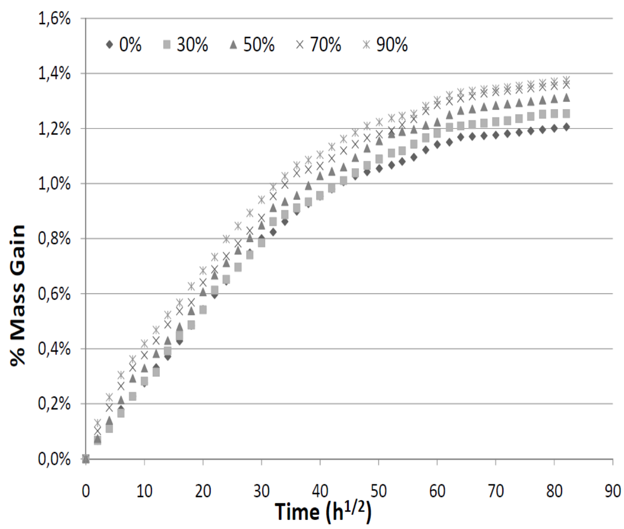

Fig. 3. Moisture absorption of different samples loaded at different levels: 0, 30, 50, 70 and 90% of SBSS.

Maximum percent mass gain and the initial slope of each sample can be obtained from the experimental curves plotted in Fig. 3. Hence, sample diffusivities are calculated using Eq. 2 and the results are presented in Table 1. Diffusivities and maximum mass gain obtained for these samples were compared to other results obtained in earlier investigations [10-12]. Although results from these studies were higher with respect to both diffusivity and M_m, present results are believed to be reasonable since both fiber volume fraction and water temperatures during the moisture conditioning are different. For instance, maximum percent mass gain at 45°C was measured to follow a linear fit with respect to fiber volume fraction as:

$$M_m = -0.0448V_f + 2.9374, \quad (3)$$

which leads, for the present samples, to an expected maximum moisture intake of around 1.49% at 45°C. Since water absorption is known to depend on conditioning temperature, M_m is expected to be lower for a moisture intake conducted at 25°C [11].

As presented in Table 2, both maximum percent mass gain and diffusivity are observed to increase almost linearly with the maximum loading applied. M_m is observed to rise by 14% from 1.21 to 1.38% after a loading of 90% SBSS is applied. Similarly, diffusivity is observed to augment by 17% from 5.04×10^{-10} to 5.88×10^{-10} m²/h. Therefore, applying various levels of three point bending loadings increases both the rate and the maximum intake of moisture absorption of fiber reinforced composites.

Short beam shear strength is often used to identify the quality of fiber matrix bonding. Thus, the applied loadings are believed to cause damage at the micro-structural level, such as cracks and loosened fiber-matrix interphase. These damages introduce additional sites for moisture accumulation. Consequently, higher loadings are expected to cause more damage and thus, allow more moisture buildup.

<u>Effect of number of loading cycles on moisture absorption</u>

The moisture absorption behavior of the composite samples loaded repeatedly is depicted in Fig. 3. Samples are loaded 1, 2, 5 and 10 times at 30% of their measured SBSS.

Maximum percent mass gain and the initial slope of each sample, obtained from the experimental curves plotted in Fig. 4, are used in Eq. 2 in order to obtain the diffusivity of each sample. Diffusivities and maximum mass gain obtained for samples subjected to different loading cycles are presented in Table 2.

A sound concordance is observed between the obtained diffusivity and maximum mass gain of the reference samples and their first set counterpart. The same remark is applicable for samples loaded once with 30% of their SBSS.

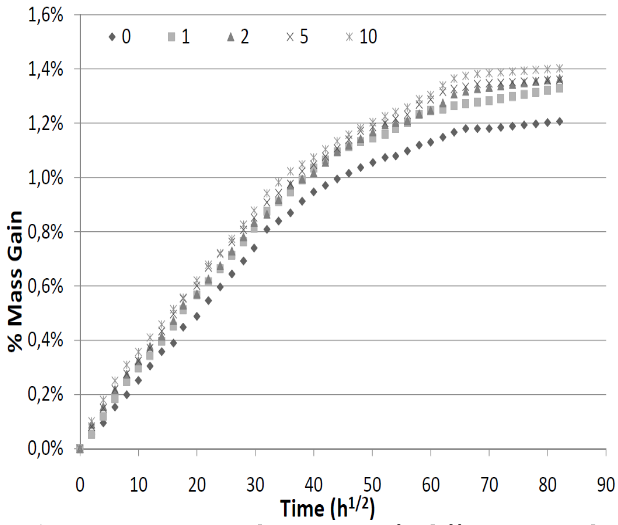

Fig. 4. Moisture absorption of different samples subjected 0, 1, 2, 5 and 10 loading cycles at 30% SBSS.

As presented in table 1, both maximum percent mass gain and diffusivity are observed to increase almost linearly with the number of loading cycles applied at 30% SBSS. M_m is observed to augment by 16% from 1.21 to 1.40% after a loading of 30% SBSS is applied 10 times. Similarly, diffusivity is observed to increase by 8% from 5.10×10^{-10} to 5.50×10^{-10} m²/h. Thus, applying repeated three point bending loadings increases both the rate and the maximum intake of moisture absorption of fiber reinforced composites.

As discussed earlier, applying three point bending loadings is believed to have caused damages within the composite samples, especially at the fiber-matrix interphase. These micro-structural damages

Table 1. Effect of loading level on maximum percent mass gain and diffusivity.

Loading level	M_m	Diffusivity ($D \times 10^{10}$ m²/h)
0%	1.21%	5.04
30%	1.25%	5.08
50%	1.31%	5.34
70%	1.36%	5.69
90%	1.38%	5.88

introduce sites for moisture accumulation. Repeated loadings can increase the damage size and initiate additional damage sites. As a result, higher numbers of loadings at any level are expected to cause more damage and thus, allow more moisture intake.

Effects of loadings and moisture on Stiffness

Stiffness is compared for samples that are loaded repeatedly; and the results are presented in Fig. 5. A stiffness reduction is observed each time an additional cycle is endured. While stiffness is observed to drop only 0.61% from between the first and second loading, the drop increases to 6.47% after 5 loadings and even 8.58% after 10 loadings. As mentioned earlier, this is believed to originate from the discussed micro-structural damages at the fiber-matrix interphase caused by the repeated loadings.

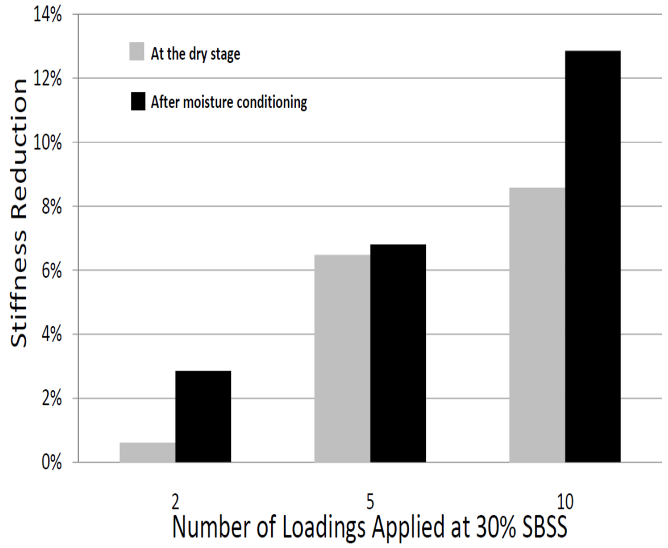

Fig. 5. Stiffness reduction before and after moisture intake for samples loaded 2, 5 and 10 times at 30%.

Moisture absorption at the interphase is expected to degrade the quality of bonds between fiber and the matrix, thus causing a reduction in both SBSS and stiffness. As predicted, stiffness reduction is observed to increase after moisture conditioning as shown in Fig. 5. Although reduction in stiffness is still higher for larger numbers of loadings, a superior drop in stiffness is observed after moisture intake. Stiffness reduction at 2 loadings went from 0.61 to 2.86% after conditioning; which represents a 3.7-fold increase. Stiffness reduction of samples loaded 10 times, on the other hand, was observed to increase by almost 50% from 8.58 to 12.85%.

In addition, stiffness reductions after moisture conditioning for samples loaded at different levels are calculated and plotted in Fig. 6.

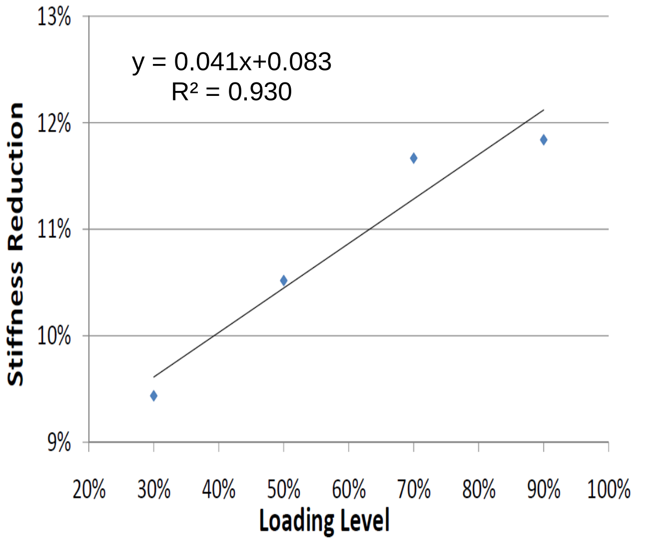

Fig. 6. Stiffness reduction after moisture conditioning for different samples loaded at 30, 50, 70 and 90%.

As depicted in Fig.6, stiffness reduction after moisture absorption is observed to augment with increasing loading level applied to the different composite samples. Stiffness reduction is found to vary almost linearly with the applied loading level going from 9.44 at 30% of the SBSS to 11.84% at 90%. An empirical linear fit is even calculated with a correlation coefficient (R^2) of 0.9304 as shown in Fig. 6. As discussed in the earlier section, moisture absorption is observed to be higher at higher levels

Table 2. Effect of loading cycles at 30% SBSS on maximum percent mass gain and diffusivity.

Number of loading cycles	M_m	Diffusivity (D x 10^{10} m²/h)
0	1.21%	5.10
1	1.33%	5.11
2	1.36%	5.15
5	1.36%	5.31
10	1.40%	5.50

of loadings most likely due to more damage occurrences at the micro-structural level. Moisture accumulation in these damages, especially at the fiber-matrix interphase, is believed to cause higher drops in stiffness for higher loading levels.

Concluding Remarks

Fiber reinforced polymer composites are highly susceptible to environmental conditions such as moisture absorption during their life cycle. While the adverse effect of moisture on composite parts is well documented, effects of repeated loading on moisture absorption of composites are not fully known. This work investigates the effect of repeated loading on moisture absorption in resin transfer molded glass/epoxy composites with 32.4% fiber volume fraction. Loading levels that correspond to 30, 50, 70 and 90% of the SBSS are applied 1, 2, 5 and 10 times, thus imparting various levels of low-cycle fatigue damage to the composite samples. A set of unloaded specimens is kept to characterize the baseline moisture absorption behavior of the composite samples. The loaded samples undergo subsequent moisture conditioning at 25°C.

Applying various levels of three point bending loadings is observed to increase both the rate and the maximum intake of moisture. Maximum percent mass gain is observed to rise by 14% from 1.21 to 1.38% after a loading of 90% SBSS is applied. Similarly, diffusivity is observed to augment by 17% from $5.04x10^{-10}$ to $5.88x10^{-10}$ m²/h.

Furthermore, moisture absorption is found to increase almost linearly with the number of applied loading. Both maximum percent mass gain and diffusivity are, again, found to increase with the increasing number of loading cycles. Maximum percent mass gain is observed to augment almost linearly by 16% after a loading of 30% SBSS is applied 10 times. An 8% increase in diffusivity is observed correspondingly.

In addition, stiffness reductions after loading and after moisture absorption are reported. Stiffness reduction that occurred after loading is linearly correlated to the number of loadings reaching 8.58% after 10 loading cycles at 30% SBSS.

Once the moisture conditioning is completed, stiffness reduction is observed to worsen significantly for all samples. An 11.84% stiffness drop is observed for samples loaded at 90% SBSS. Similarly, a 12.85% in measured for samples loaded 10 times at 30% SBSS.

These results are believed to be applicable to similar fiber reinforced composites susceptible of undergoing moisture absorption during their life cycle.

References

1. Y. K. Hamidi, S. Dharmavaram, L. Aktas, M. C. Altan, *J. Eng. Mater. & Tech.*, **131**, 1 (2009)
2. Y. K. Hamidi, L. Aktas, M. C. Altan, *J. Thermop. Comp. Mater.*, **21**, 141 (2008)
3. V. Rohatgi, N.Patel, J. L. Lee, *Polym. Comp.*, **17**, 161 (1996)
4. A. D. Mahale, R. K. Prud'Homme, L. Rebenfeld, *Polym. Eng. & Sci.*, **32**, 319 (1992)
5. N. C. W. Judd, W. W. Wright, *SAMPE J.*, **14**, 10 (1978)
6. A. A. Goodwin, C. A. Howe, R. J. Paton, *ICCM-11 Proc., Austr. Comp. Str. Soc.*, **IV**, 11 (1997)
7. K. A. Olivero, H. J. Barraza, E. A. O'Rear, M. C. Altan, *J. Comp. Mat.*, **36**, 2011 (2002)
8. B. D. Harper, G. H. Staab, R. S. Chen, *J. Comp. Mat.*, **21**, 280 (1987)
9. C. Hoppel, T. Bogetti, J. F. Newill, *Proc. Amer. Soc. Comp.*, 1094 (2000)
10. L. Aktas, Y. K. Hamidi, M. C. Altan, *Proc. IMEC&E, ASME, Pap. # 39223* (2002)
11. L. Aktas, Y. K. Hamidi, M. C. Altan, *J. Mat. Proces. & Manuf. Sci.*, **10**, 239 (2002)
12. L. Aktas, Y. K. Hamidi, M. C. Altan, *J. Mat. Proces. & Manuf. Sci.*,, **10**, 255 (2002)
13. Y. K. Hamidi, L. Aktas, M. C. Altan, *Polym. Comp.*, **26**, 614 (2005)
14. Y. K. Hamidi, L. Aktas, M. C. Altan, Comp. Sci. & Tech., **65**, 1306 (2005)
15. Y. K. Hamidi, L. Aktas, M. C. Altan, *J. Eng. Mat. & Tech.*, **126**: 420 (2004)

16. H. S. Choi, K. J. Ahn, J. D. Nam, H. J. Chun. *Comp. A*, **32**,709 (2001)
17. Z. A. Mohd Ishak, N. C. Lim. *Polym. Eng. & Sci.*, **34**,1645 (1994)
18. L. E. Doxsee, W. Janssens, I. Verpoest. *J. Reinf. Plas. & Comp.*, **10**, 645 (1991)
19. D. W. Suh, M. K. Ku, J. D. Nam, B. S. Kim, S. C. Yoon. *J. Comp. Mat.*, **35**, 264 (2001)
20. C. Hoppel, T. Bogetti, J. F. Newill. *Proc. Amer. Soc. Comp.*, 1094 (2000)
21. W. C. Tucker, R. Brown, *J. Comp. Mat.*, **23**:787 (1989)
22. Tucker W. C., S. B. Lee and R. Rockett, *J. Comp. Mat.*, **27**, 756 (1993)
23. M. Akay, S. Kong Ah Mun, A. Stanley, *Comp. Sci. & Tech.,* **57**, 565 (1997)
24. J. Viña, E. A. Garcia, A. Argüelles, I. Viña, *J. Mat. Sci. Lett.*, **19**, 579 (2000)
25. R. Roy, B. K. Sarkar, N. R. Bose, *Bull. Mater. Sci.*, **24**, 87 (2001)
26. M. Akay, *Comp. Sci. & Tech.*, **28**, 359 (1990)
27. S. Kaushal, K. Tankala, R. M. V. Rao, G. K. Kishore, *J. Mat. Sci.*, **26**, 6293 (1991)
28. W. Krolikowski, *SPE J.*, **20**, 1031 (1964)
29. A. Djumaev, K. Takahashi, *J. Mat. Sci.*, **29**, 4736 (1994)
30. G. Li, S. S. Pang, J. E. Helms, *Polym. Comp.*, **21**, 686 (2000)
31. P. Davies, F. Pomies, L. A. Carlsson, *J. Comp. Mat.*, **30**, 1004 (1996)
32. F. U. Buehler, J. C. Seferis, *Comp. A*, **31**, 741 (2000)
33. J. Crank, Mathematics of Diffusion, Oxford at The Clarendon Press (1956)
34. C. H. Shen, G. S. Springer, *J. Comp. Mat.*, **10**, 2 (1976)
35. P. C. Upadhyay, A. Mishra, *J. Reinf. Plas. & Comp.*, 9, 335 (1990)
36. ASTM D 2344/D 2344M-00, *Standard Test Method for Short-Beam Strength of Polymer Matrix Composite Materials and Their Laminates.*
37. ASTM D 5229/D 5229M-92, *Standard Test Method for Moisture Absorption Properties and Equilibrium Conditioning of Polymer Matrix Composite Materials.*