

Environmental Effects on E-Glass Fiber Reinforced Polymers

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Abstract

As of late, glass fiber-reinforced polymers (FRPs) have become appealing substitutes for aluminum, concrete, and steel when a high strength to weight ratio or corrosion or ease of handling are needed. FRPs are also known for being able to be engineered to meet that mechanical properties needed for a given project by selecting a certain fiber size or type of resin, etc. FRP applications will expose the polymer to environmental effects, such as humidity, water, or UV rays. However, limited research has been done and is available on the fundamental behavior of FRP composites in the long range. FRP composites are used in a variety of industries. The military, automotive and aerospace fields can directly benefit from the results of this project. The project has two principal components: The experimental portion of the project involves gathering evidence from executing experiments on coupon sized specimens; while the analytical portion of the project uses the data collected to prepare a model for life prediction.

1. Introduction to my study

Glass can be defined as a product of inorganic materials fusing together cooling to a rigid condition without crystallization (Hashemi 622). Glass workers have been working with glass for over 5000 years. They started by making glass beads and other forms of ornamentation. Over 4000 years later, man figured out a way to create small glass vials by blowing glass. (Shrager, 210). According to Shrager, there are three main steps to producing glass. First glass sand, small crystals of silica, is melted. Second the glass is shaped while it is in the viscous state. Finally the shaped glass is cooled in a control method (211). Shrager went on to say that glass is chemically stable because all atoms in glass are fully oxidized. He went on to say that “all the electron orbitals are fully occupied at every energy level by strong bonding” ensuring that glass is immune to decay. The tightly covalently bonded electrons in glass make glass a poor conductor of electricity. Shrager went on to say that “large gaps in electron energies make glass an excellent insulator”, especially “in a dry environment” (214). Glass is also naturally strong and is practically elastic and is harder than many types of steel. Glass also has high tensile and compressive strength (214-215). So these facts lead to the question why exactly is glass transparent when it is just as hard, if not harder, than metals and metalloids?

Glass has some characteristics that make it a unique material. Glass' internal structure is homogeneous. This provides only two main obstacles for light, which are the surfaces of the glass. This allows for about ninety percent of light to pass through (214-215). Hashemi notes that as glass goes from solid glass to a super-cooled liquid to liquid when heated. It is also important to note that as the temperature increases, so does the specific volume of the glass. Glass also possesses interesting qualities at room temperature. Because of how difficult it is to get rid of intermolecular bonds during its liquid configuration, glass is not crystalline. Because glass' viscosity is so high at room temperature, it would take a million years for it to crystallize and act like a regular solid (211).

When cooling, the exterior of glass cools more rapidly than the interior, causing stress to develop on the glass (Shrager, 212). This happens because in the molten state, sand

crystals breaks up and forms rings or strings of SiO₄ tetrahedral in irregular patterns (211). The larger grouping of tetrahedral form and the decrease in kinetic energy cause a decrease in viscosity and shrinkage (212). Network modifiers, as defined by Hashemi, are oxides that break up the glass network. He went on to explain that alkali and alkaline earth oxides can be added to silica glass, lowering its viscosity, allowing it to be formed and worked with easily. “The oxygen atoms from these oxides enter the silica network at points joining the tetrahedral and break up the network, producing oxygen atoms with unshared electron. The sodium (Na⁺) and potassium (K⁺) ions from the Na₂O and K₂O do not enter the network but remain as metal ionically bonded in the interstices of the network. By filling some of these interstices, these ions promote crystallization of the glass. (623)”

Glass can be classified into to different types. Electrical or e-glass is a type of glass used to produce glass fibers for composites. This type of glass is most commonly used for continuous fibers. It is usually a lime- aluminum- borosilicate glass with oxygen or low sodium and potassium levels (Hashemi, 651). Strength or s-glass is a name for other types of glass fibers, such as s-glass, d-glass, a-glass, ECR glass, ultra pure silica fibers, hollow fibers, and trilobal fibers (ASM vol. 21, 27). There are many uses for s-glass. This particular type of glass is mostly used with aerospace and military applications due to its strength (Hashemi, 651).

There are many different types of glass fibers. They can be broken into two categories: the low cost general-purpose fibers and the premium special- purpose fiber (ASM vol. 21, 27). Letter designations and descriptions for some of the types of fibers are shown in Table 1.

Table 1: Letter designations and descriptions for some of the types of fibers

Name of Fiber	Letter Designation	Description of Purpose of Fiber
Electrical	E	Low electrical conductivity
Strength	S	High strength
Chemical	C	High chemical durability
Modulus	M	High stiffness
Alkali	A	High alkali/soda lime glass
Dielectric	D	Low dielectric constant

The fiber forming process is described in great detail in the American Society of Materials Handbook in volume 21. “Glass melts are made by fusing (co-melting) silica with minerals, which contain the oxides needed to form a given composition.” To prevent crystallization, the molten mass is cooled rapidly (27).

Materials are often subjected to failure and degradation so it is important to address these issues also. According to the American Society of Materials volume 19, there are four principle fracture modes. The first one to be addressed is ductile fracture. It is important

to note that a ductile material is one that will deform reversibly to a certain point then break. The second type of failure that will be addressed is brittle. A general definition of brittle failure is a fracture that takes place at stresses below the net section yield with very little observable plastic deformation and minimal absorption of energy (ASM vol. 19, 371). Cleavage is the most worrisome type of brittle failure (7). “For metallurgists, cleavage is often referred to as brittle failure and dimple rupture is considered ductile fracture. However, these terms must be used with caution, because many service failures occur by dimple rupture, even though most of these failures undergo very little overall plastic deformation from an engineering point of view. (5)” It is hypothesized by the author that there is little plastic deformation because while the material is in service, it is heated causing the bonds to weaken. With weaker bonds, the material is more susceptible to failure.

When a material is in service, is also predisposed to fatigue failure. Failure of a material due to the repeated application of loads that aren't large enough to cause failure with a single application (Bentur, 152). The American Society of Materials volume 19 goes into further detail on how this type of failure occurs. First noted is cyclic deformation. These are causes of internal damage in the form of dislocated debris. Secondly is the formation of a crack after sufficient damage has been caused by the cyclic loading. Last noted is the propagation of the crack to a size where it becomes unstable for the loading being applied. It is important to introduce some terminology related to fatigue loading. Sigma max (σ_{max}) is the maximum stress in the loading cycle while it is reasonable to assume that sigma minimum (σ_{min}) is the minimum stress in the loading cycle. Sigma M (σ_M) is the mean stress which is taking the average of the minimum and maximum stress as expressed in equation 1.

$$\sigma_M = \frac{\sigma_{max} + \sigma_{min}}{2} \quad (1)$$

The stress ratio (R) is shown in equation 2.

$$R = \frac{\sigma_{min}}{\sigma_{max}} \quad (2)$$

It is also important to note that Benture also said that “when sigma max and sigma min are both tensile or compressing ... this is referred to a pulsating stress” (157). This pulsating stress was used in this project.

This project involved tests and procedures that should also be addressed. The Dynamic Mechanical Analysis (DMA) is one of these. As defined by Anasys, Dynamic Mechanical Analysis “measures the mechanical properties of materials while they are subjected to a periodic stress, usually applied sinusoidal” (1). By using this method of testing, one can find the phase angle (Δ), the storage modulus (E'), the loss modulus (E'') and the dynamic (or complex) modulus (E^*). Tangent (Δ) also comes in handy as the damping factor (3). According to Polydynamics, the storage modulus can be defined as the ratio of the shear stress to shear strain (10). This relates to the elasticity of the

sample. The loss modulus is a measurement of the polymer's viscosity (6). The dynamic (or complex) modulus is the ratio of stress to strain under vibratory conditions. This is a property of some what elastic materials (7). Damping, as defined by Gu, is "the mechanism by which the ordered mechanical energy of a material of a system is dissipated as disordered thermal energy to its surroundings as an irreversible process. (8)" Gu goes on to explain that dampening characteristics tend to depend more on the temperature, frequency, the orientation of the fiber, and the matrix properties, and not on the amplitude of the strain (22). The data collected from the Dynamic Material Analysis is supposed to be time dependent data (Shranger, 18).

Thermal Mechanical Analysis (TMA) is similar to the Dynamic Material Analysis method. TMA is the most sensitive method to find Tg. It also allows detection of transitions in materials. TMA also allows one to study cures and detects changes in volume. This testing method also allows one to detect crystalline and crosslink density. Both the Thermal Mechanical Analysis and the Dynamic Material Analysis methods can detect the rate and degree of cure among other material characteristics (UNESCO, 24).

The Vacuum Assisted Resin Transfer Molding or VARTM method was used in this project to create the samples that were tested. This method pulls resin in from a feed tube and evenly distributed it in the perform (Army, 2). The American Society of Materials notes in volume 21 of its handbook that "reinforcing fabric is placed over the area under consideration and the entire area is encapsulated in a vacuum bag. In a variant, the outer layer of fabric in contact with the bag is partially cured prior to placement in order to assume good surface (1094). The ideal vacuum according to the Army is thirty inches mercury (2).

2. This is why I studied it

I wanted to explore this project for the summer of 2007 for many different reasons. As a Civil engineering undergraduate student specializing in Structures, I embrace any opportunity I am offered to explore strengthening existing structures, bridges, and buildings. I feel as if the advancements made in this focus area of Civil Engineering are appreciated by the field as a whole due to the diversity of its applications. It is also important to note that articles are published in major concrete and material journals on the advancements in this focus area. It is also my plan to continue my studies as a graduate student further investigating the link between Structural Engineering and Material Science and Engineering. This project was the perfect combination of my passion for Material Science and my knowledge of Structural Engineering.

3. The significance of the study is

3.1. Problems and Possible Solutions

This project not only investigates e-glass fibers and how these fibers can strengthen a resin coupon, it also investigates interfacial bonding. According Jang, "a variety of fiber surface treatments and modification techniques have been developed to control the interfacial bonding of glass fiber. (979)" Interfacial bonding is good because according to Gu "it is widely recognized that interfacial bonding of the composite can be related to a change in energy absorbing ability" (1). This change is typically positive, making the

composite stronger because the energy is evenly distributed. However, Gu is quick to note that interfacial bonding does have its negative points. “In some cases, a weak interface is desirable to promote fiber pull-out, hence providing a tougher composite system (21).

Controlling interfacial adhesion seems to be prospective accomplishment by the industry. This is because impact-related problems are believed to be related to the degree of association between the matrix and the fiber. The many prospective advantages to these materials cannot be fully implemented due to the material’s vulnerability to impact damage (Jang, 979). “The degree of fiber impregnation is critical for the success of reinforcement. Improper impregnation decreases the tensile strength and elastic modulus of fiber composite because of the voids between fibers, increases water absorption, and decreased the degree of conversion. (Kim, 278)” Kim points out that the degree of fiber impregnation is critical to the strength of the composite because voids in the fiber will be susceptible to water. Water can easily the voids and expand and contract with fluctuating temperature changes that the composite could be subjected to easily. Gu goes on to comment on the effects of tensile strength saying that “tensile strength of the composite depend on the ability of the composite to effectively transfer load from the matrix to the fiber via shear at the interface” (Gu, 1).

3.2. Creation of the Panels

One of the main things that were accomplished this summer was the creation of the test panels. They consisted to three basic configurations. One was resin only panels only, another was unidirectional FRP composite panels, and the last were cross-ply FRP composite panels. Of the latter two, the layers would be 8 to 10 layers thick. These multiple arrangements are to evaluate the fundamental role of the fiber lay-up in the degradation rate. These panels are to be tested for their water content after being submerged in fresh water at different temperatures. They are to be submerged for 50, 100, 200, 300, 400, and 500 days of fresh water submergence. The samples will also be subjected to other tests, such at tension, impact, fatigue, dynamic mechanical analysis and thermal mechanical analysis. The Impact tests were to be done by the ASTM Standard D 5420. The fatigue tests were to done by ASTM Standard D 3479 and the DMA tests are to be done by ASTM Standard E 1640.

3.3. Analytical Model Development

The main part of this study is to make a prediction model for the degradation of composite materials. The proposed computational tool will be based on the observed material behavior of aged and samples that are not aged subjected to the various methods of testing as listed above. This project will develop a model at a micro level to simulate degradation mechanisms for the composites under consideration. All this will require the use of non-linear finite element analyses, which is already available with the ABAQUS software package.

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