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# Durability of Flax FRPs Exposed to Accelerated Environmental Conditions

D. Hristozov[1], L. Wroblewski[1], P. Sadeghian[2]

[1] Former Undergraduate Student, Penn State Harrisburg University, Middletown, USA

[2] Assistant Professor and Canada Research Chair, Dalhousie University, Halifax, Canada

## ABSTRACT

It is well known that synthetic fiber reinforcements, such as glass fibers, elevate the mechanical properties of polymer materials. Considering the synthetic material's renewability challenges, natural fibers, such as flax can provide promising mechanical behavior as a more renewable resource. However, the durability of natural fibers against moisture and other environmental conditions is not well-known. In this paper, aggressive accelerated tests were conducted in order to investigate the durability of flax fiber-reinforced polymer (FRP) composites in comparison to glass FRPs. The initial process was making FRP sheets out of two layers of fabrics and vinyl-ester resin; and then cutting them into dumbbell-shaped specimens for tensile test. The specimens were put under three different environmental conditions namely water, salt water, and alkaline solutions. Some specimens were kept in an air dry condition as control specimens. The temperature of the solutions was controlled at 20, 50, and 60 C. The durability testing was conducted at 500, 1000, 2000, and 3000 hours exposure. The results show that flax FRPs have similar and even slightly better durability performance in terms of tensile strength retention percentage in comparison to glass FRPs.

## 1. INTRODUCTION

Classic fiber materials for fiber-reinforced polymer (FRP) composites are usually made of non-renewable resources (i.e. synthetic fibers), and typically emit significant greenhouse gases during fabrication. At the end of their service life, they are incinerated, sent to landfills, or recycled to materials with less quality, usually by energy-intensive methods. Thus, there is a major need to (i) limit the use of non-renewable materials by using more renewable ones, (ii) reduce pollution and energy costs of material production, and (iii) use materials that have more potential after service life or demolition. Considering synthetic materials' lack of renewability [1], this research was conducted on natural fibers from renewable resources with comparable mechanical properties to synthetic fibers. Natural fibers extracted from plants (e.g. flax, hemp, jute, and etc.) are good example of renewable materials and offer several economical, technical, and ecological advantages over synthetic fibers. FRP composites made of natural fibers have been extensively researched for the past two decades [2]. Due to the relative large quantity, low cost of raw material, low density, high specific properties, and positive environmental profile, natural fibers have been considered as prospective substitutes to synthetic fibers, specifically glass fibers [3]. Despite of positive characteristics, natural fibers have some negative characteristics. They are highly hydrophilic and their mechanical and physical properties are strongly dependent on the climate, location, and weather; so it is difficult to predict their respective composite properties and failure mechanism [4]. In terms of long-term performance, there are drawbacks about their durability against moisture and other environmental conditions [5-7].

In the literature, there are limited durability studies on FRP composites made of natural fibers. Recently, Yan et al. [8] used accelerated UV weathering to study the durability of flax FRPs for civil engineering applications as an alternative to steel reinforcement. In tension, the strength and initial elastic modulus were reduced by 29.9% and 34.9% after weathering; respectively. In flexure, the strength and initial elastic modulus were reduced by 10.0% and 10.2%; respectively. The effect of weathering on tension properties had a much greater effect. The scanning electron microscope showed that weathered specimens failed in the interface of fibers and matrix while the control specimens failed in the fibers.

More recently, Mak et al. [9] investigated the short- and long-term performances of flax FRP composite and compared its behavior to glass FRP. The impact of manufacturing method, namely wet layup and vacuum bag molding, and number of layers on short-term mechanical properties was also examined. Long-term performance was determined through environmental aging in salt water containing 3.5% salt content by weight, where flax FRP coupons were subjected to 23, 40, and 55 C water for up to a maximum of 365 days. All mechanical properties and degradation were assessed through tension tests. Results showed that using the vacuum bag process, flax FRP showed a strength and modulus 18 and 36% higher, respectively, than wet layup specimens. As the number of layers increased from one to five, the strength and modulus also increased but stabilized at three layers. After 365 days of conditioning at 23, 40 and 55 C, wet layup specimens showed a strength retention of 81, 73, and 69%, respectively.

In the current research, accelerated durability tests were conducted in order to investigate the long-term mechanical performance of FRP composites made of flax fibers exposed to a variety of environmental conditions. For comparison, similar tests were conducted on FRP composites made of glass fibers. The specimens were exposed to three different environmental conditions, namely water, salt water, and alkaline solutions. In addition, control specimens were kept in an air dry condition for comparison. The temperature of the specimens was controlled at three levels and the mechanical tests were conducted after four different exposure duration to the environmental conditions.

## 2. EXPERIMENTAL PROGRAM

A total of 490 specimens (245 flax and 245 glass FRPs) were prepared and tested under uniaxial tensile loading [10] (Table 1). Initially, FRP sheets were made of two layers of flax/glass fabrics and vinyl-ester resin as a matrix for the fibers. After cutting the sheets into 25 mm wide and 165 mm long strips, the strip-shaped specimens were immersed into different environmental conditions, namely water (W), salt water (SW, 3.5% salt by weight), and alkaline (AL, PH=12.5) solutions. In addition, control specimens were kept in an air dry condition for comparison. The temperature of the specimens was controlled at three levels, namely 20 C (room temperature), 50 C, and 60 C.

The mechanical tests were conducted after 500, 1000, 2000, and 3000 hours exposure to the environmental conditions. For each case, five identical specimens were prepared and exposed into the environmental conditions. After the exposure, the specimens were cut into dumbbell-shaped specimens and tested based on ASTM D638 [11] standard. A universal testing machine with a 25 mm gauge length extensometer sensor was used to provide a stress-strain curve for each specimen. Changes in weight and physical appearance of the specimens were also recorded over the exposure periods to study the moisture diffusivity of the composites. Temperature and PH of the solutions were controlled during the tests. Specimens and solutions were kept in sealed containers to control evaporation and exposure for maintaining the chemical concentration of the solutions.

Table 1: Test matrix

| Exposure (days/hrs) | Air dry (AD) | | | Water (W) | | | Salt water (SW) | | | Alkaline (AL) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 20 C | 50 C | 60 C | 20 C | 50 C | 60 C | 20 C | 50 C | 60 C | 20 C | 50 C | 60 C |
| Control | 5 | - | - | - | - | - | - | - | - | - | - | - |
| 21/500 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| 42/1000 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| 83/2000 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| 125/3000 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| Total | 245 flax and 245 glass FRP specimens | | | | | | | | | | | |

## 3. TEST RESULTS

### 3.1 Water Absorption

Figure 1 shows the variation in weight gains of flax and glass FRPs at three temperatures of 20, 50, and 60 C after 21, 42, 83, and 125 days (i.e. 500, 1000, 2000, and 3000 hours) immersing in water. The weight gains were calculated based on oven dry weight and saturated surface dry weight of each specimen. The weight gains are the average of five identical specimens and the bars show a standard deviation lower and higher the average values. The figure shows almost three times water absorption for flax FRPs in compare to glass FRPs. The loss of mass due to higher degradation at higher temperature could be the reason of a lower gain under 60 C than under 50 C.

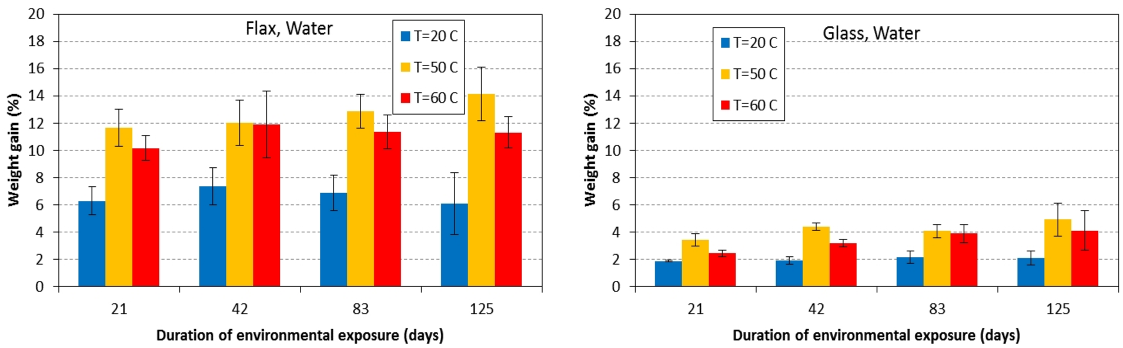


Fig. 1: Variation in weight gain of flax and glass FRPs

### 3.2 Tensile Strength

Figures 2 and 3 show the variation in tensile strength of flax and glass FRPs with type and duration of environmental exposure. The average actual thickness of flax and glass FRP specimens before exposure to the environmental solutions was 2.11 and 2.33 mm with standard deviation of 0.28 and 0.12 mm. For consistency, the nominal thicknesses of 1.0 mm and 1.5 mm were uses for flax and glass FRP specimens, respectively. The nominal thicknesses selected based on the actual thickness measurements of dry fabrics.

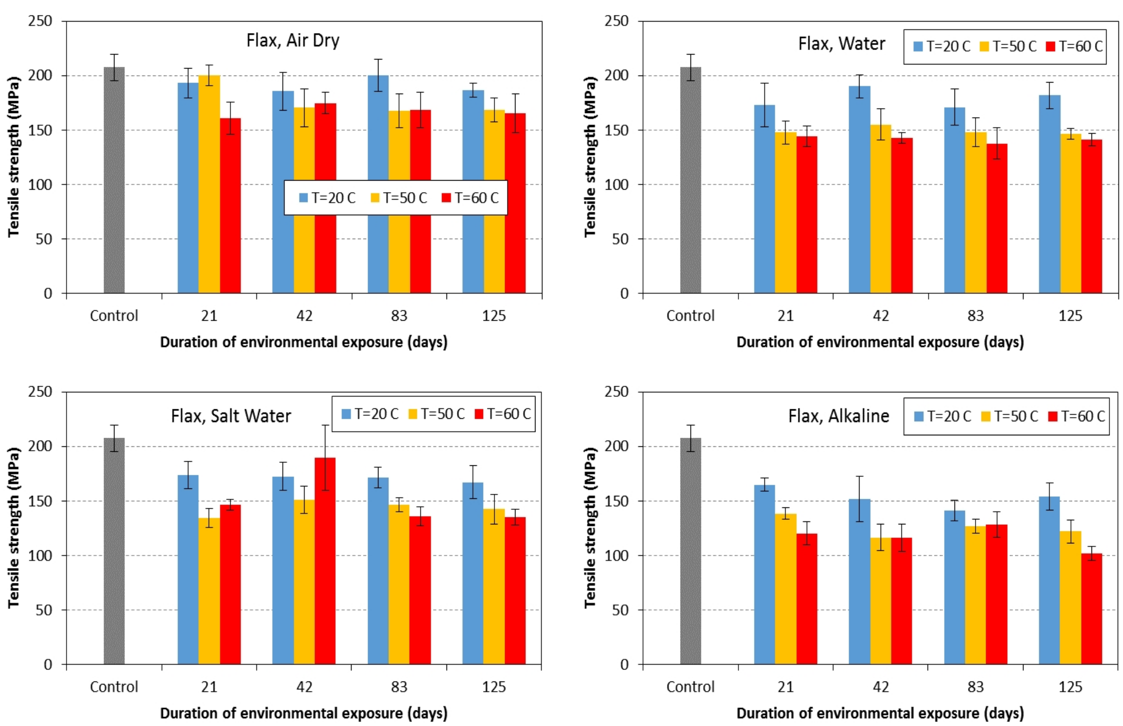


Fig. 2:Variation in tensile strength of flax FRPs

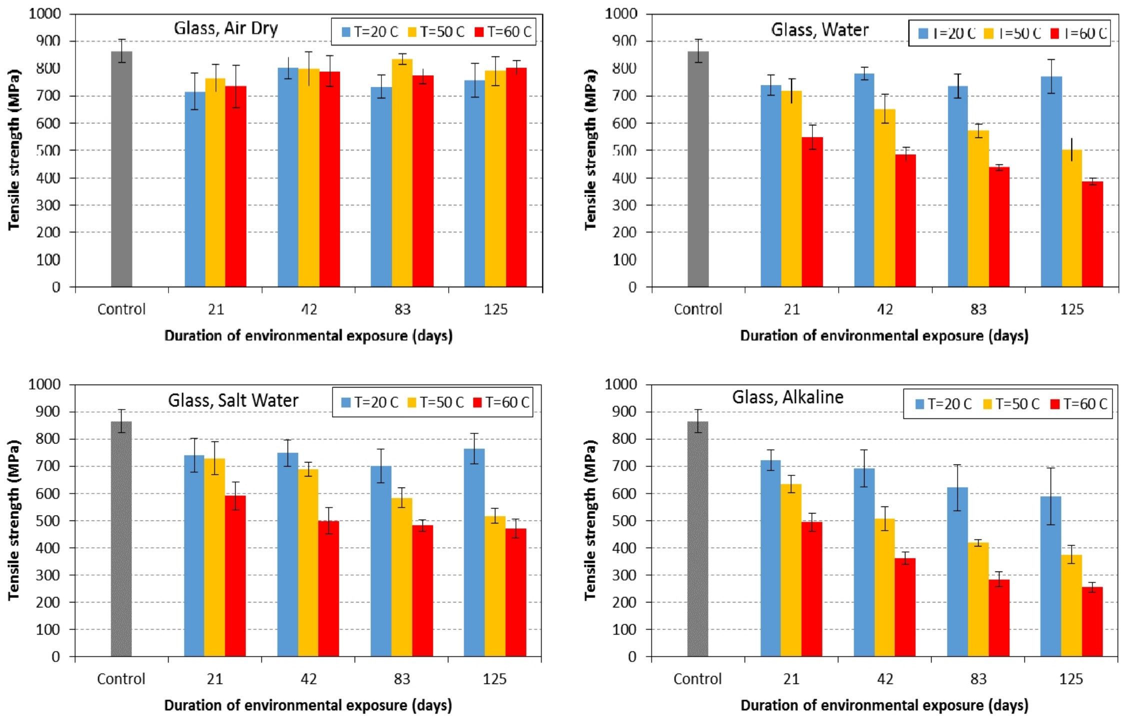


Fig. 3: Variation in tensile strength of glass FRPs

Figure 4 shows the tensile strength retention of flax and glass FRPs in alkaline solution. Figures related to other conditions are not shown here due to lack of space. The figures show that after 125 days (3000 hours) of immersing in water at 20, 50 and 60 C, the tests showed a weight gain of 2.1, 4.9, and 4.1% for glass FRPs; and 6.1, 14.1, and 11.3% for flax FRPs; respectively. Moreover, the tensile strength, modulus of elasticity, and rupture strain were studied to determine the degree of deterioration of the composites.

After 3000 hours of conditioning at 20, 50 and 60 C, flax FRPs showed a strength retention of 88, 71, and 68% in water; 81, 69, and 65% in salt water; and 74, 59, and 49% in alkaline; respectively. At the same conditions, glass FRPs showed a strength retention of 89, 58 and 45% in water; 88, 60, and 54% in salt water; and 68, 43, and 30% in alkaline; respectively. As shown in Fig. 4, the tensile strength retention in alkaline solution decreases with increasing exposure time and temperature. This is logical for glass FRPs as glass fibers are vulnerable to alkaline environments, however for flax FRPs there is an initial drop and then the strength retention stays constant around 60-70% with slight variation. More research with longer exposure is needed to understand this phenomenon completely.

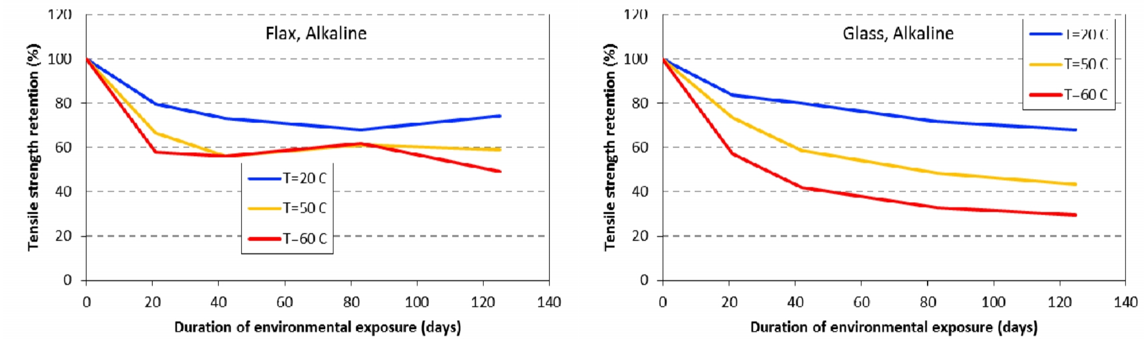


Fig. 4: Variation in tensile strength retention of flax and glass FRPs

### 3.3 Initial Elastic Modulus

Figure 5 shows the variation in initial elastic modulus of flax and glass FRPs with temperature and duration of exposure to alkaline solution. The figures show that the modulus of both flax and glass FRPs slightly increase in air dry condition. This can be explained by the post-curing of the resin over time and the increasing of the cross-links density which is reflected in an increase of stiffness of the composites. However, after immersing to alkaline solution, the initial elastic modulus of flax FRPs decreases up to 20% and that of glass FRPs remain almost constant.

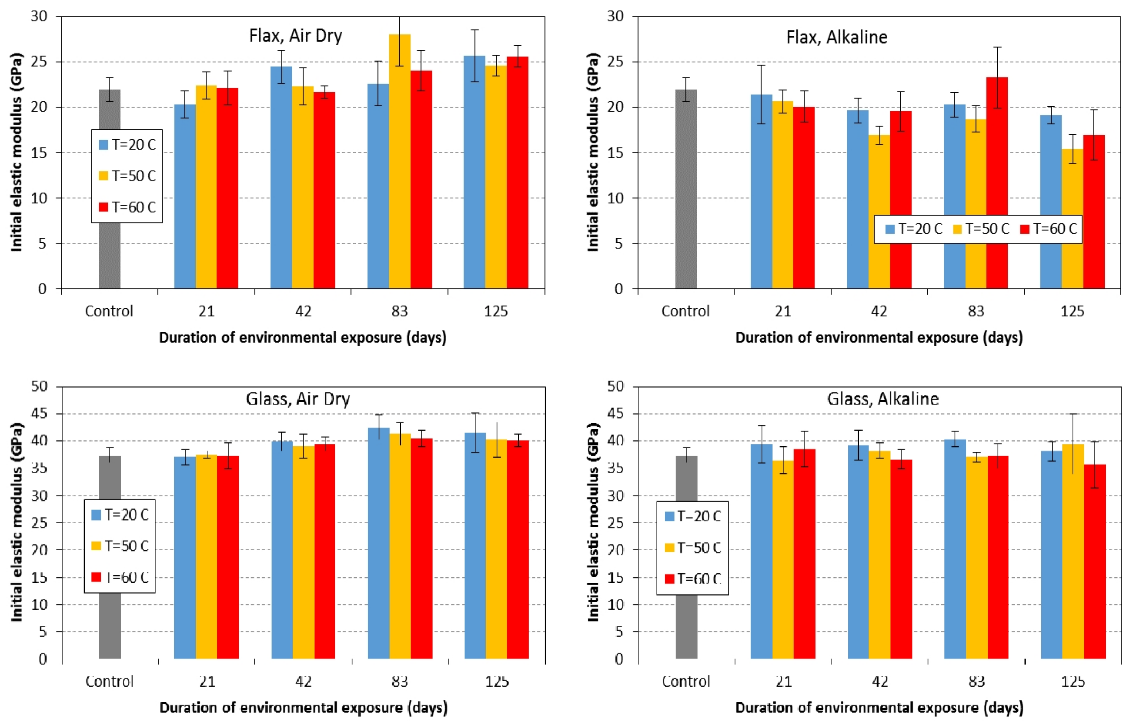


Fig. 5: Variation in initial elastic modulus of flax and glass FRPs

### 3.4 Stress Strain Behavior

Figure 6 shows the stress-strain curves of flax and glass FRPs exposed to alkaline solution at 60 C for 125 days (3000 hrs) in compare to control specimens. The dotted lines represent the average initial elastic modulus of each five specimens. The figures show that glass FRPs have almost linear behavior before and after exposure to alkaline solution. Flax FRPs have a bi-linear behavior in both air dry and alkaline environment, however alkaline exposed specimens are more flexible than air dry specimens at the same level of loading.

## 4 CONCLUSION

A total of 490 specimens were prepared and tested under uniaxial tensile loading. All specimens were made of two layers of flax/glass fabrics and vinyl-ester resin as a matrix for the fibers. The specimens were immersed into different environmental conditions, namely water, salt water (3.5% salt by weight), and alkaline solutions (PH=12.5). In addition, control specimens were kept in an air dry condition for comparison. The temperature of the specimens was controlled at three levels, namely 20, 50, and 60 C. The mechanical tests were conducted after 500, 1000, 2000, and 3000 hours exposure to the environmental conditions. After 3000 hours of immersing in water at 20, 50 and 60 C, the tests showed a weight gain of 2.1, 4.9, and 4.1% for glass FRPs; and 6.1, 14.1, and 11.3% for flax FRPs; respectively. Moreover, the tensile strength, modulus of elasticity, and rupture strain were studied to determine the degree of deterioration of the composites. After 3000 hours of conditioning at 20, 50 and 60 C, flax FRPs showed a strength retention of 88, 71, and 68% in water; 81, 69, and 65% in salt water; and 74, 59, and 49% in alkaline; respectively. At the same conditions, glass FRPs showed a strength retention of 89, 58 and 45% in water; 88, 60, and 54% in salt water; and 68, 43, and 30% in alkaline; respectively. Despite of almost three times water absorption of flax FRPs in compare to glass FRPs, flax FRPs showed slightly higher strength retention with an average of 23%. The results show that the long-term mechanical behavior FRP composites made of flax fibers is not worse than FRP composites made of glass fibers.

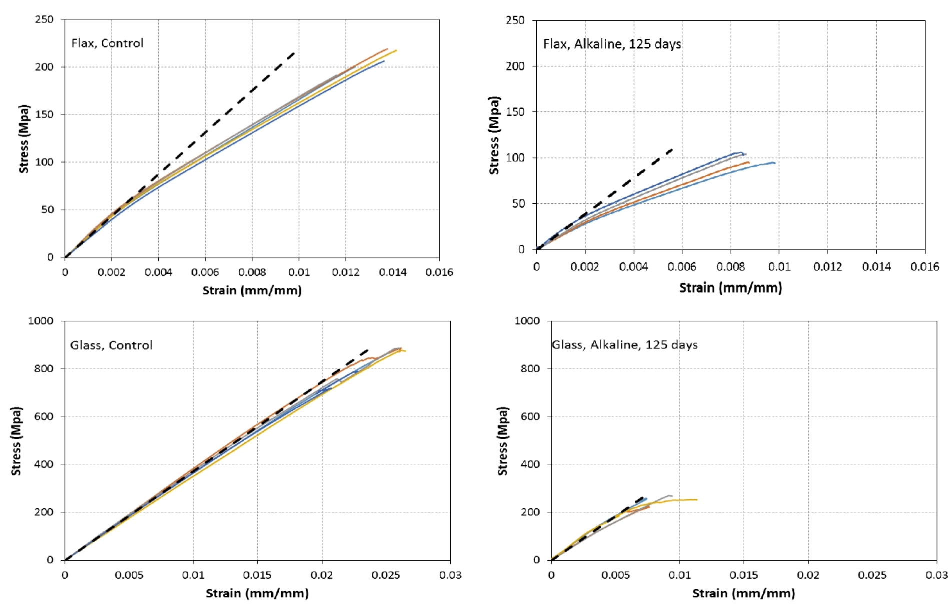


Fig. 6: Stress-strain curves of flax and glass FRPs exposed to alkaline solution (T=60 C) in compare to control specimens

## 5. ACKNOWLEDGEMENTS

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