INFLUENCE OF MOISTURE ON E-GLASS FIBER COMPOSITES

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Abstract. *Over the years, great interest has been shown for the use of glass fiber-reinforced plastic (GFRP) as reinforcement in a polymer matrix of structural composites such as tubing, tanks and reservoirs, used in high and low pressure applications. The advantages of using glass fibers over other synthetic fibers in composite reinforcement are: low cost, low density, good mechanical properties and good thermal insulation properties. The main purpose of this study was develop laminar composites using tensile and three-point bending tests, in which the composites were submitted to the dry state, to the moist state in distilled water and to the moist state in seawater. Innumerable points were observed as possible influencers in the mechanical response of the product when faced with extreme environmental adversities, such as low moisture absorption by the glass fiber. The laminar composites proposed in this study involve synthetic fiber (E-glass) reinforcements in an orthophthalic polyester matrix. The experimental investigation included uniaxial tensile and three-point bending tests to determine the mechanical properties of the final product, as well analysis of moisture absorption until laminate saturation. The composite plates were industrially manufactured using the hand-lay-up lamination process and contained 7 layers of E-glass fiber mat. The proposal of the study involved the collaboration of a company that already used these laminates as tubing and/or reservoirs, replacing other high-cost synthetic fiber composites. The results obtained show that the moisture absorption of the laminates developed was not significantly influenced by the types of tests they were submitted to.*

Keywords*: E-glass fiber composites, Moisture, Distilled water, Seawater, Mechanical properties.*

1. INTRODUCTION

Composite materials are composed of two or more different materials combined to provide mechanical properties unattainable by each material individually (Mendonça, 2005). Composites are being increasingly used in new industrial areas owing to properties such as low density, high specific strength, high elasticity module, large chemical inertia, and because they enable the manufacture of geometrically complex parts (Gibson, 2000). In recent years there has been keen interest worldwide in the development of new technologies that allow the use of more environmentally friendly products. In this context we observed one of the few disadvantages of synthetic plastic materials, which have raised questions regarding their non-biodegradability and difficult recycling, a situation that results in the large accumulation of these materials in landfills and in the environment itself.

Its numerous advantages make glass fiber the most widely used fiber in composites with a polymer matrix, owing mainly to its low cost and high tensile strength. The disadvantages of this fiber are related to low module elasticity, self-abrasiveness and low fatigue resistance when added to composites (Neto, 2006; Pardini, 2006).

Polymer composite materials stand out for their low density and easy molding, in addition to their good thermal and electrical insulation. Their structure can be made of polymers, which, in turn, are formed by macromolecules composed of covalent bonds joined to one another by weak intermolecular interactions. This ultimate structural characteristic limits the temperature of polymers, compared to other types of materials. In most composite applications, polymers act as a reinforcement clustering matrix, in the form of an agglutinant (the matrix), enabling the reinforcements to transfer mechanical forces among one another in an integrated way. Composite materials are generally composed of a combination of materials, and the possible combinations in the structuring of composites depend on the desired structures. Thus, polymer resins are used to agglomerate and structure composites composed of high mechanical strength fibers and filaments.

If we take the composites obtained from a polymer matrix as an example, we observe that carbon, aramid and E-glass fibers are the most widely used commercial reinforcement fibers. These fibers provide high stiffness and strength to the components that use them. Polymer matrices (thermorigid and thermoplastic), despite having low specific mass (~1g/cm³), are much less resistant and rigid than fibers. This peculiarity results in the mechanical properties (rupture strength and elastic constants) of the polymer composites used in engineering applications being significantly influenced by both fiber orientation (direction angle) with respect to mechanical requests and the volume fractions of their individual components. This dependency also occurs in the hygrothermal properties of the polymer composites, such as heat conduction, thermal dilatation and moisture absorption, among others (Gibson, 1994).

The combination of the physical, mechanical and chemical properties of components of a composite that provides the desired characteristics to the final product must be performed with good knowledge of the properties of each component, thus always requiring a thorough study of the characteristics of each material individually (Aquino, 2005; Bledsky, 1999).

The structural application of composite materials has grown considerably in recent years owing to the improved manufacturing processes involved as well as the conception of new reinforcement configurations (fabrics) and laminar structures. Furthermore, the growth in plant fiber-based composites such as sisal, jute, banana, and curauá fibers, among others, underscores the fact that their main application is in the elements submitted to small and medium forces. When compared to synthetic fibers, natural fibers generally exhibit low mechanical performance (Mohanty et al., 1995; Aquino, 2005).

Currently, the structural performance of synthetic composites still exceeds that of natural composites in many aspects. However, with the growing need to protect the environment against the widespread environmental degradation caused by industrial processes, and to minimize dependence on non-renewable resources such as oil, thereby promoting sustainable development, the use of renewable plant-based raw materials has been increasing in recent years. To date, with rare exceptions, the production of synthetic materials has caused environmental problems, and their use in composites, mainly in thermorigid matrices, has contributed to the generation of difficult-to-recycle waste. On the other hand, materials, such as bones, teeth, bamboo and several species of wood, have also displayed exceptional mechanical performance in a number of aspects. These studies, in addition to representing a possible solution to existing environmental problems and to the scarcity of raw materials, may contribute to the improvement of current synthetic composites (Neto, 2006; Pardini, 2006).

The configuration (proposed here for E-glass fiber composites) for the use of E-glass fiber in the dry state was performed to obtain good mechanical properties in the final product. Moreover, this laminar structure was submitted to moisture, in one case with seawater (presence of salinity) and in the other to a moist state with distilled water, that is, without its minerals.

This study observed the influence of moisture absorption on the mechanical properties of laminar structure composites (7 layers of E-glass fiber).

Given that the aim is the development of new materials, a detailed study involving the mechanical properties of strength and stiffness must be the starting point for this investigation. Determining the influence of moisture absorption on these properties becomes essential for possible applications of the configurations in tubing and/or reservoirs.

2. MATERIALS AND METHODS

An industrially manufactured laminar composite structure was developed using the hand-lay-up technique, characterized by simple composite manufacturing procedures. This process is carried out by placing and piling up of reinforcement, in this case in the form of mats, using orthophthalic polyester resin, which, compared to isophthalic resins, is more rigid and requires longer gelification time. The manual molding process gives rise to composites with little structural compromise and which have a reinforcement volume fraction of around 40%.

The composite used here is characterized by a laminar structure, reinforced with E-glass fiber mats submitted to the dry state, the moist state with distilled water and the moist state with seawater. Exposure time of the laminate composite to moisture was 290 days, in which salt and distilled water was replaced at monthly intervals. Figure 1 shows the raw material used to obtain the laminate, where letter (a) refers to the mat and letter (b) to the resin used.

The process was initiated by treating the surface of the mold with a demolding agent to remove the part after the curing process. Resin impregnation with a hardening agent (catalyzer) was performed on each overlapping reinforcement layer. The thickness of the molded component was obtained by the number of overlapped layers. Curing was done at ambient temperature.

Moisture was measured in the samples by weighing them in the dry state and comparing this result with the weight after a period of time submersed in water (distilled or seawater, depending on the sample). The weighing period was varied to have the largest number of weighings at the start (when absorption is more intense), decreasing when the absorption curve became less steep.

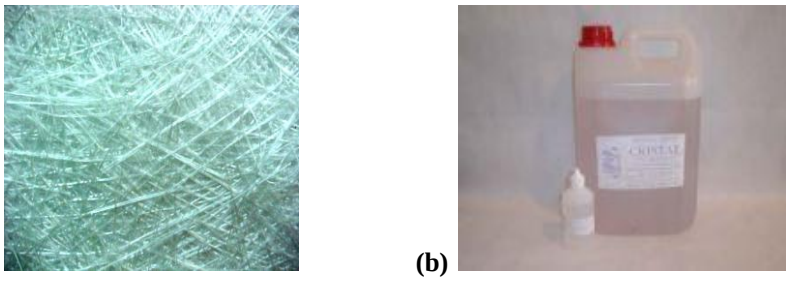

Figure 1. Materials used in the composites: (a) E-glass fiber mats, (b) orthophthalic polyester resin.

The configuration of the laminated composite was done using 7 layers of E-glass fiber mat (450 g/m^2). Figure 2 shows the outline of this configuration.

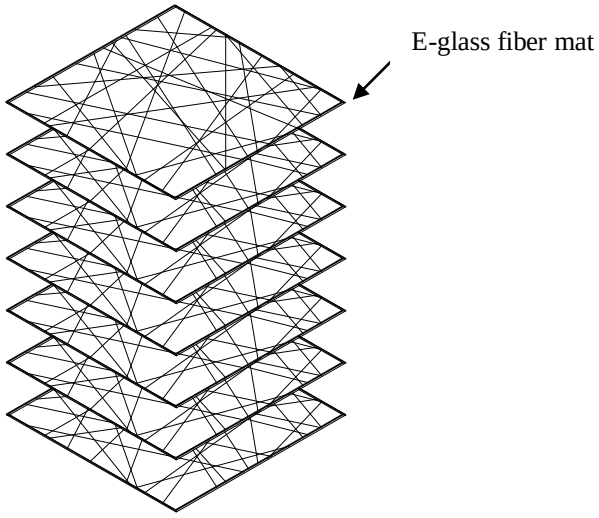

Figure 2. Composite configuration.

The sizes of the test specimens (TS), shown in figures 3 and 4, and the specifications of uniaxial tensile and three-point bending tests followed ASTM D3039-00 (2000) and ASTM D790-90 (1990) standards, respectively. The tests were conducted at ambient temperature, in a SHIMADZU AG-1 universal testing machine.

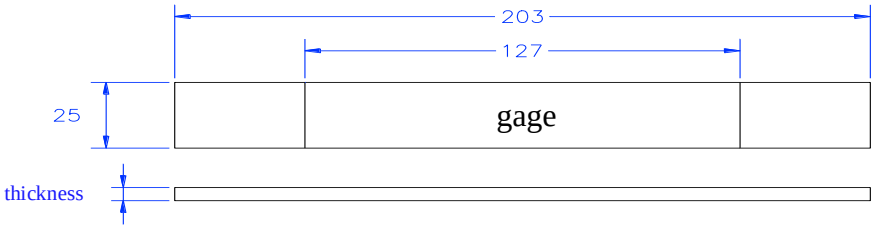

Figure 3: Schematic drawing of the TS for the uniaxial tensile test.

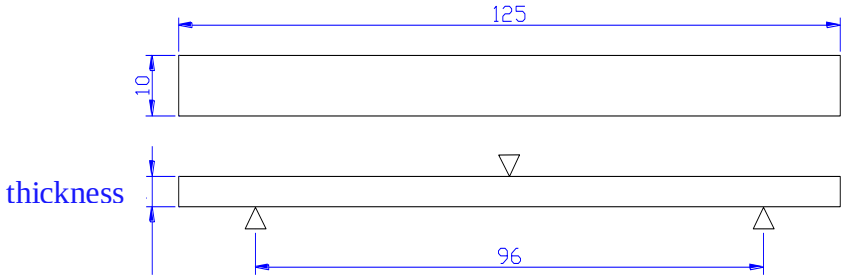

Figure 4: Schematic drawing of the TS for the three-point bending test.

3. RESULTS AND DISCUSSION

3.1. Tests of moisture absorption in the laminates

The laminates were immersed, one in distilled water and the other in seawater, in which saturation absorption was observed after 146 days with 0.94% and 0.70% of moisture absorption, respectively (Figure 5). The literature shows that the mean saturation time of glass fiber-based composite material is between 2 and 3 months (Margaria et al., 1997; Aquino, 1996). Glass fiber composites also exhibit greater absorption in distilled water than in seawater.

The curves in figure 5 show that in the first hours of absorption, both distilled water and seawater are absorbed by the composite at the same rate. However, this begins to change after 0.1% absorption, where a difference can be observed between the curves, that is, distilled water is more absorbed by the samples than seawater is, demonstrating that salinity affects water diffusion in the composite only after a certain period of time.

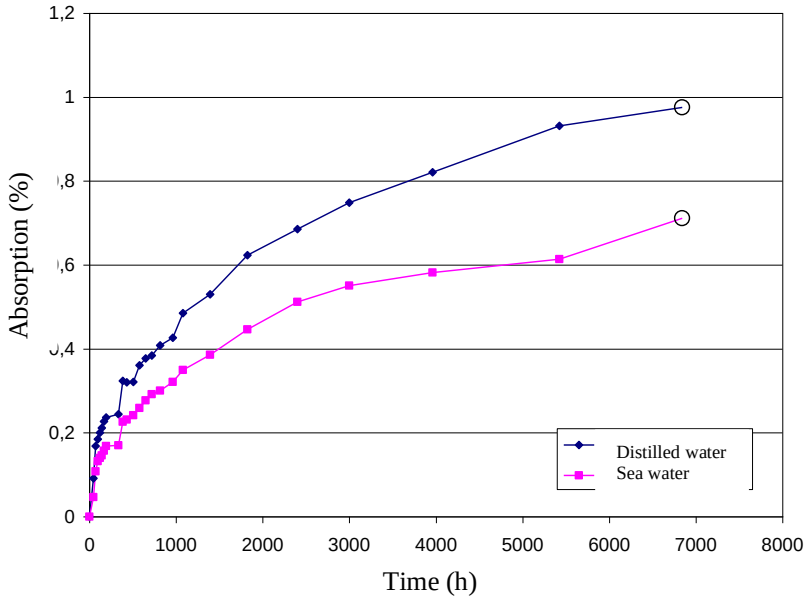

Figure 5. Percentage absorption versus immersion time.

The lower moisture immersion by the material in salt water may be explained by the accumulation of large NaCL ions inside the material, mainly on the fiber surface, hindering subsequent water diffusion (Davies et al., 2001). This effect is only apparent after an initial diffusion value (0.1%) and increases with immersion time.

Another factor that might influence the absorption process is the void content in the composite, given that these voids may accumulate water, forming concentrated salt solutions; in this study, however, we were unable to determine the void percentage, thus ruling out analysis of this variable. Factors such as laminate configuration and quality of laminate interfaces also influence the absorption process; however, it is difficult to measure the effect of these variables separately.

3.2. Tensile test analysis of the laminate in a dry state

The stress versus strain curves of the laminates, shown figure 6, were submitted to tensile testing in the dry state, where it can be seen that the material exhibits linear behavior until final fracture.

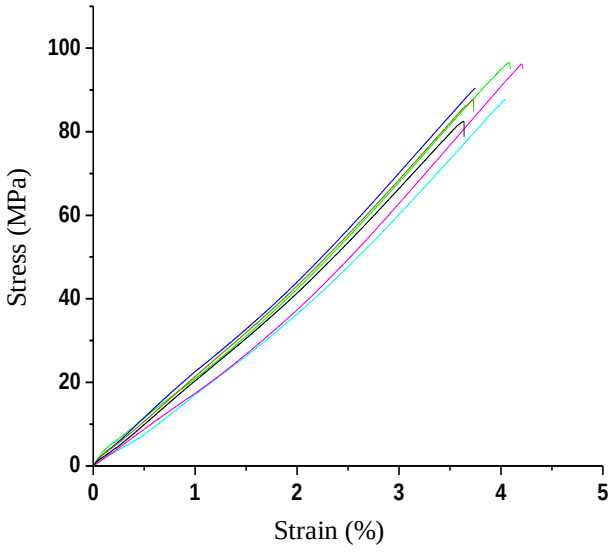

Figure 6. Stress versus strain curves – Uniaxial tensile test of the laminate in the dry state.

The curves show a tendency toward linear behavior, typical of most composites with thermofixed matrices and synthetic fibers. The fracture was fragile, occurring within the useful area of the test specimen.

The mean values obtained for the Tensile ultimate stress test, for the longitudinal elasticity module (measured in the direction of the applied load) and for rupture strain are shown in table 1, as are variation percentages.

Table 1. Mechanical properties of the laminate in the dry state – Uniaxial tensile.

Mechanical properties	Mean values	Dispersions (%)
Tensile ultimate stress	85,45 MPa	± 11,32
Elasticity module	3,93 GPa	± 0,22
Rupture strain	4,02%	± 0,29

The values in Table 1 show a slight variation of the results.

3.3. Analysis of three-point bending tests of the laminates in the dry state

Figure 7 shows the stress versus deflection graph obtained in the three-point bending test to which the glass fiber was submitted.

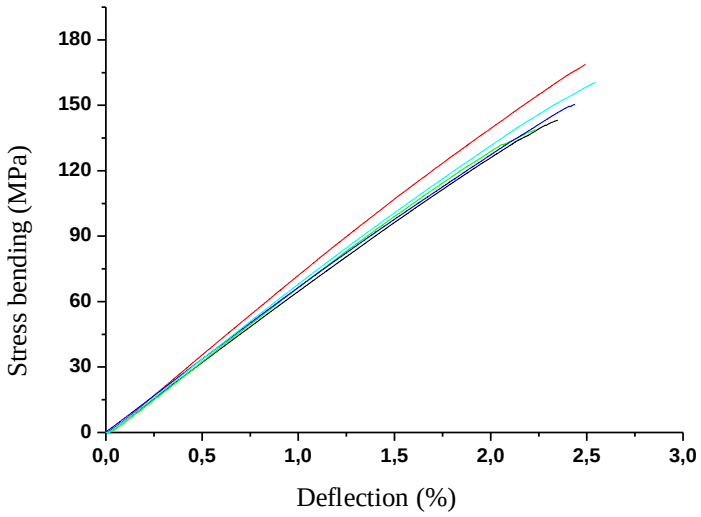

Figure 7. Stress versus deflection curve – Three-point bending of the laminate in the dry state.

A comparison with the uniaxial tensile test shows that the fiber laminate under the three-point bending displayed a more marked linear behavior until final fracture. This behavior is characteristic for many types of synthetic fiber-reinforced polymer composites, with both laminar and sandwich structures (Oliveira, 2005; Aquino, 1997).

The mean ultimate stress bending values obtained for the elasticity module and for maximum deflection are shown in table 2, along with the variation percentages.

Table 2. Mechanical properties of the laminate in the dry state – Three-point bending.

Mechanical properties	Mean values	Dispersions (%)
Ultimate bending stress	152,39 MPa	± 8,97 %
Elasticity module bending	6,81 GPa	± 5,8 %
Rupture strain bending	2,43 %	± 5,76 %

Although bending variation was greater than that of tensile, a slight variation in the results can still be observed in the strain and stiffness of the material, where the greatest variation was found for material resistance (11% for tensile strength and 8.9% for bending).

3.3. Tensile tests of the laminates in the dry state

Figure 8 shows the stress versus strain curves of the laminates submitted to the moist state with distilled water (a) and seawater (b). Similar to what was observed in the dry state, these graphs show that neither of the laminates underwent significant changes in curve linearity until final fracture of the test specimens.

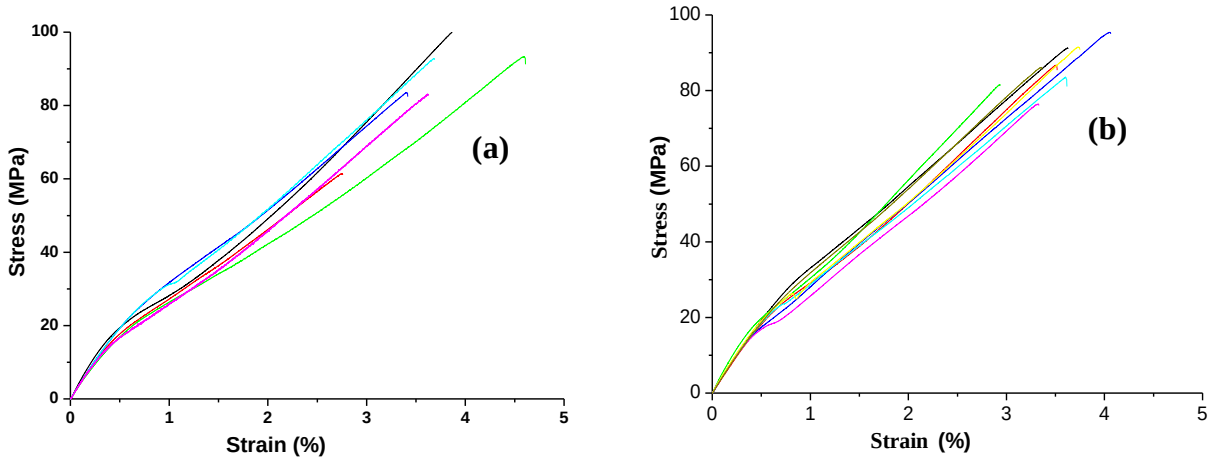

Figure 8. Stress versus strain curves – Uniaxial tensile strength in the composites saturated in distilled water (a) and in seawater (b).

Figure 9 shows the mean values of (a) tensile ultimate stress and (b) the tensile elasticity module of moist composites. These values correspond to mean values at the moment of fracture and a slight decrease in the mechanical properties of the laminate in the dry state can be observed, mainly in stiffness, but this decrease was not significant. This reduction in mechanical properties is due to the low capacity of the laminated composite to absorb moisture (non-hydrophilic). The laminate tested for tensile strength in distilled water and in seawater obtained an ultimate tensile strength of 81.5 MPa and 86.2 MPa, respectively and with respect to the tensile elasticity module, obtained 2.7 GPa and 3.2 GPa, . The decrease in strength and stiffness was greater in the composite immersed in distilled water (4.6% in strength and 29.6% in stiffness) and this result is due to the higher percentage of water absorbed by the composite than that absorbed by the composite immersed in salt water, where a loss of 18.6% in stiffness and a gain of 0.87% in strength were observed. These results show that increased moisture significantly influenced only material stiffness and that this influence was greater with the use of distilled water.

A greater variation in the ultimate tensile strength results was observed in distilled water (around 47.1%), practically twice the variation calculated in the laminate saturated in seawater and 4 times that of the laminate in the dry state. An explanation for this fact may be related to the voids found in the TS of the composites, which can occur heterogeneously. When these particular samples have points with a large amount of voids concentrated at a specific point, they drastically lose their strength when immersed in water.

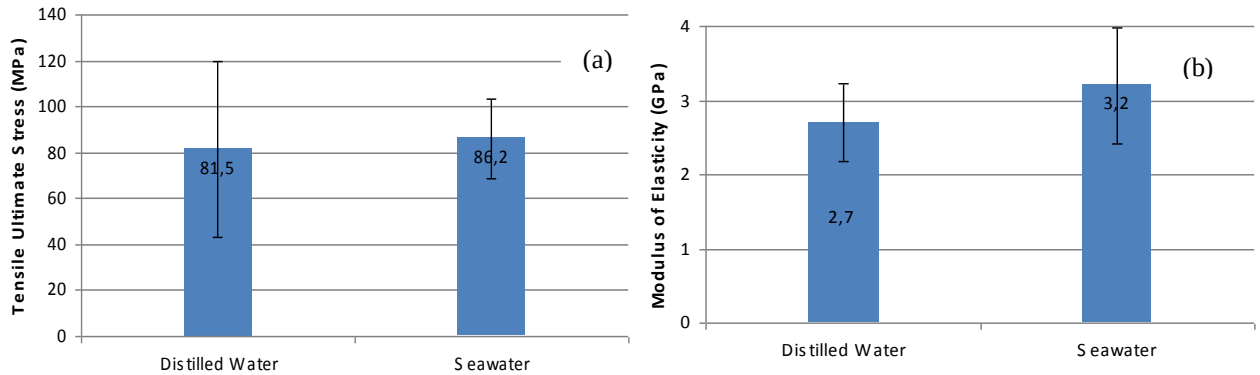

Figure 9. (a) Tensile ultimate stress and (b) Elasticity module of the laminate composites submitted to the tensile test in the dry state.

Table 3. Mechanical properties of the laminate in the moist state in distilled water – Uniaxial tensile strength.

Mechanical properties	Mean values	Dispersions (%)
Tensile ultimate stress	81,53 MPa	± 47,1 %
Elasticity module	2,77 GPa	± 19,61 %
Rupture strain	3,54 %	± 31,67 %

Table 4. Mechanical properties of the laminate in the moist state in seawater – Uniaxial tensile strength.

Mechanical properties	Mean values	Dispersions (%)
Tensile ultimate stress	86,2 MPa	± 19,94 %
Elasticity module	3,2 GPa	± 24,32 %
Rupture strain	3,51 %	± 27,83 %

3.4. Analysis of the three-point bending test of the laminates in the moist state

In these tests, as occurred for the three-point bending test in the dry state, no early shear fracture, caused by the presence of moisture in the composites, was observed in the laminate.

Figure 10 shows the Stress versus Deflection curves obtained for the laminates saturated in distilled water and seawater, tested for bending in the moist state. These graphs demonstrate that, similar to what occurs in the dry state, there is linear behavior at the onset of loading, but after a determinate percentage of deflection, some of the samples lose their linearity, showing that the viscoelastic behavior of the resin is more marked for bending loads.

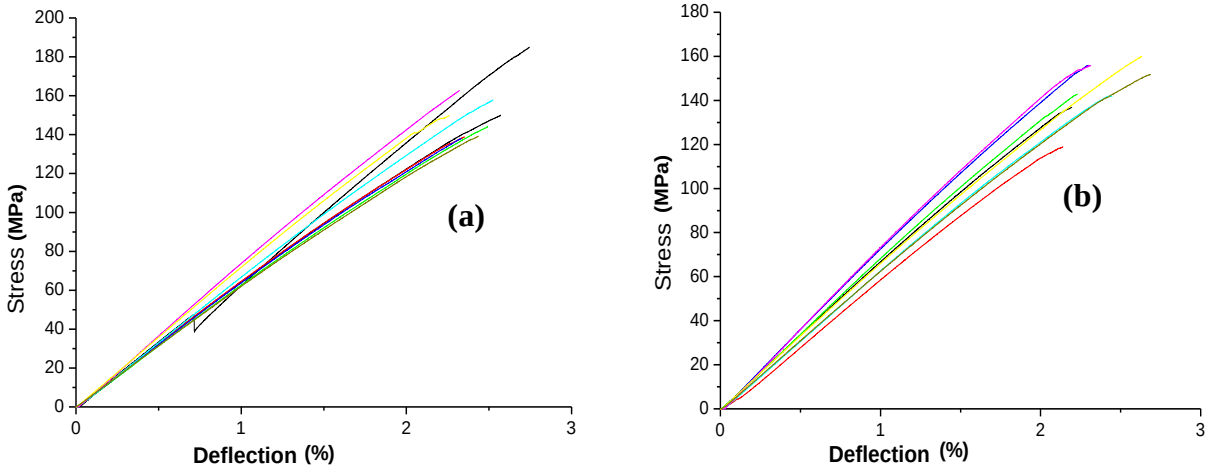

Figure 10.Stress versus Deflection curves of the laminates (a) laminates saturated in distilled water and (b) laminates saturated in seawater.

Figure 11 shows (a) the ultimate stress bending and (b) the bending elasticity module of the composites in the moist state, in the moist state, in distilled water and in seawater, under three-point bending testing. These values correspond to the mean values of all the test specimens at the moment of fracture.

In the comparative study between the dry and moist states, no significant decrease in strength and stiffness can be observed in the two laminates with the presence of moisture. A 4.4% loss in ultimate stiffness and 2.6% in laminate stiffness was recorded and when the dry laminate was compared with the laminate in a moist state, in seawater and in distilled water, a loss of only 2.8% was found in stiffness, without any significant loss of strength.

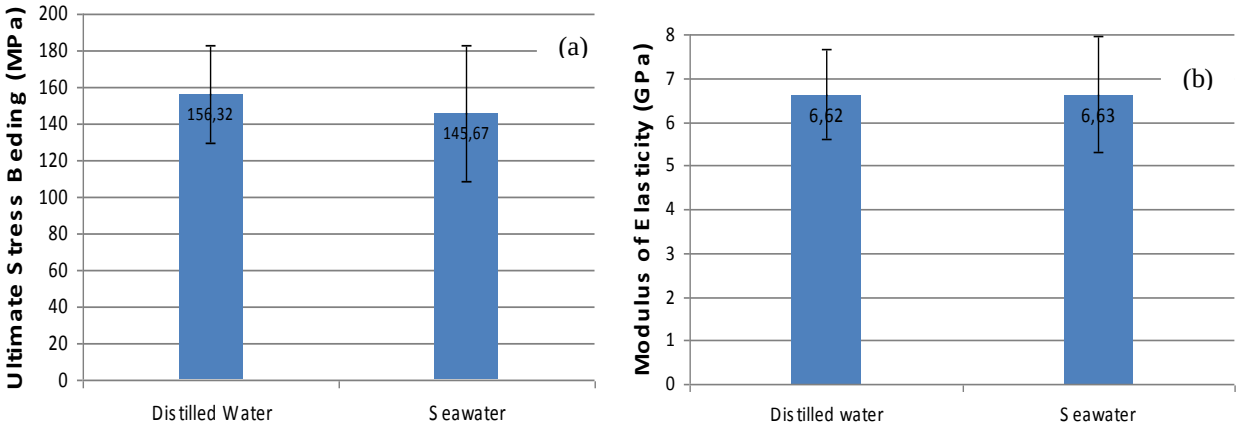

Figure 11. (a) Ultimate stress bending (b) Elasticity module of the laminates submitted to three-point bending tests in a moist state.

Another factor that can be analyzed is the variation in results. Table 5 and 6 show greater variation compared to the material in the dry state (table 2), with a variation in ultimate bending strength in seawater of 25%, nearly three times greater than that obtained in the dry state (8.9%). These results demonstrate that salinity had some influence on the variation in the bending results.

Table 5. Mechanical properties of the laminate in the moist state in distilled water – Three-point bending.

Mechanical properties	Mean values	Dispersions (%)
Ultimate bending stress	156,32 MPa	± 17,03 %
Elasticity module bending	6,62 GPa	± 15,6 %
Rupture strain bending	2,59 %	± 13,73 %

Table 6. Mechanical properties of the laminate in the moist state in seawater – Three-point bending.

Mechanical properties	Mean values	Dispersions (%)
Ultimate bending stress	145,67 MPa	± 25,53 %
Elasticity module bending	6,63 GPa	± 20,05 %
Rupture strain bending	2,37 %	± 20,45 %

4. CONCLUSIONS

Based on the study conducted, a number of conclusions can be drawn about the use of glass fiber in the presence of moisture for the composite laminates studied here.

1- The laminar structure, in a dry state, exhibits mechanical properties of strength and stiffness, both uniaxial tensile and three-point bending, that are compatible in intensity with the configuration already in use in industry. This fact makes its application as a structural element feasible;
2- The laminated composite submitted to the moist state in distilled water absorbed more moisture (25% more), compared with the laminate immersed in seawater, even though we observed no type of early fracture or more than one type of fracture in the test specimens assayed, but rather a very localized fracture that did not significantly affect the regions far from the final fracture.
3- The data obtained from the tensile test confirmed a greater decrease in strength and stiffness in the composite immersed in distilled water, owing to the larger percentage of water absorbed, compared to the composite immersed in seawater. An increase in moisture significantly influenced only material stiffness and this increase was greater with the use of distilled water.
4- The variation in ultimate bending strength of the laminate saturated in distilled water is practically double that of the laminate saturated in seawater and four times that of the dry laminate. An explanation of this fact may be

related to the voids in the material, test specimens with larger voids or even a larger amount of these voids being influenced by the moisture, making these test specimens lose strength and stiffness to a more significant degree.

5- A comparative study of the composite submitted to three-point bending, between the dry and moist states, shows that there is no significant decrease in the strength and stiffness of the two laminates with the presence of moisture. There is only a considerable variation in the ultimate strength of the laminate saturated in seawater compared to the dry state, demonstrating that salinity influenced this variation in results.

6- An analysis of the results obtained for the laminated composites shows that the proposed lamination is viable in the moist state, mainly in small and medium-sized structural applications involving axial loads. For applications involving bending loads saturated in distilled water and in seawater, a more detailed study with a hybrid laminate in small and medium-sized structural applications is currently being developed.

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