Mechanical behavior of glass fiber-reinforced polyester in a humid environment

Comportamento mecânico do poliéster reforçado com fibra de vidro em um ambiente úmido

Comportamiento mecánico del poliéster reforzado con fibra de vidrio en un entorno húmedo

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ABSTRACT
Glass fiber composite materials have been well known in certain maritime applications for a long time, being used in several applications in different fields. The characteristics of Glass fiber-reinforced Polyester (GFRP) depend on the contained fibers, the matrix used, and the fiber-to-total volume ratio. GFRP is a polymer material used in various fields; it is generally preferred for its ease of installation and its very long lifespan, even in the presence of aggressive fluids. The aim of this research is to study the evolution of mechanical properties (tensile strength and flexural strength) of GFRP preserved in different environments such as open air (control), drinking water, and seawater (harsh environment). Additionally, tests on GFRP are conducted through chemical characterization studies or SEM observation of the resin. Lastly, GFRP is considered to be chemically stable for a conservation period of one year in seawater. Finally, despite the conservation of GFRP for a year in a humid and sulphate environment, we note that the connection between the fibers and the matrix is in good condition, or the conservation environment has no influence on the GFRP composite.

Keywords: Tensile. Flexural. E Fibers. C Fibers. Seawater.
aplicaciones en diferentes campos. Las características del poliéster reforzado con fibra de vidrio (GFRP) dependen de las fibras contenidas, de la matriz utilizada y de la relación fibra/volumen total. El GFRP es un material polimérico utilizado en diversos campos; generalmente se prefiere por su facilidad de instalación y su muy larga vida útil, incluso en presencia de fluidos agresivos. El objetivo de esta investigación es estudiar la evolución de las propiedades mecánicas (resistencia a la tracción y resistencia a la flexión) del GFRP conservado en diferentes ambientes como aire libre (control), agua potable y agua de mar (ambiente agresivo). Además, las pruebas sobre el GFRP se realizan mediante estudios de caracterización química o la observación de la resina por SEM. Por último, se considera que el GFRP es químicamente estable durante un periodo de conservación de un año en agua de mar. Por último, a pesar de la conservación del GFRP durante un año en un ambiente húmedo y sulfatado, constatamos que la conexión entre las fibras y la matriz está en buen estado, o sea que el ambiente de conservación no influye en el composite GFRP.

Palabras clave: Tracción. Flexión. Fibras E. Fibras C. Agua de Mar.

1 INTRODUCTION

The main advantages of applying fiber-reinforced polymer (GFRP) include low weight, high stiffness-to-weight and strength-to-weight ratios, easy installation, potentially high overall durability, resistance to corrosion and chemical attacks, controllable thermal expansion and dimensional stability, good fire resistance, and fast curing times (Benmoktane et al., 1995; Carra et al., 2014). The mechanical properties of composite materials depend on the contained fibers (type, quantity, and direction), the matrix used, and the fiber-to-total volume ratio (Naama, 2007). Traditionally, E-glass is the most commonly used with a polyester or epoxy resin matrix. This glass is less strong and slightly less rigid than other commonly available glasses, but it is significantly less expensive (Chalmers, 1994). The reinforcement of a composite is linked to the percentage of fibers, or the fiber-to-resin ratio, usually being over 50% fibers by weight, as well as the type of fibers and the orientation of fibers concerning the direction of loads (Adrian et al., 2010).

The effects of humidity and temperature on glass fibers can cause damage and reduce their expected durability. The degradation mechanisms of glass fibers in water or alkaline solutions can be classified into two categories: leaching and chemical attack. In the leaching reaction, glass fibers form a water layer in which alkaline ions are leached out and replaced by protons (H⁺), and the leaching of
alkaline oxides (sodium and potassium oxides) on the surfaces of glass fibers leads to the formation of microcracks. The second significant reaction is called "etching," in which hydroxyl ions break the Si-O-Si structure (Chen et al., 2007; Silva et al., 2014). The only reason PRF is not used in marine applications is due to the potential long-term mechanical property degradation and inter-laminar shear strength reduction caused by seawater environment effects (Garcia-Espinel et al., 2014).

Silva et al. in 2014 concluded that higher temperatures cause more severe degradation of the tensile strength of PRF (for all specimens exposed to temperatures from 35°C to 65°C) (Silva et al., 2014). Kim et al. in 2008 studied PRF specimens and found that the edges of glass fibers corrode (specimens immersed in an alkaline solution at 40°C for 60 days), and this damage is mainly due to alkaline and moisture attack, which also affected the fiber-matrix interface (Kim et al., 2008). Akay et al. in 1997 found that absorbing 1% humidity led to a reduction of 5%, 4%, and 2% in compression, shear, and flexural strength, respectively (Ray et al., 2014). Results from bending tests conducted by Poodts et al. in 2013 on plates with dimensions (100X300X4)m³ preserved in seawater at a temperature of 15°C showed that the ultimate stress and ultimate strength of vinyl ester-E glass plates are higher than those of polyester-E glass plates. Moreover, a regression of 20% and 6% in ultimate strength and ultimate stress, respectively, was recorded for polyester resin plates compared to vinyl ester resin at the age of 22 weeks of preservation (Poodts et al., 2013).

Pultruded glass fiber-reinforced polymer composites are at risk of degradation and aging due to electrical stresses, dynamic loads, creep, and extreme environmental issues. In recent studies, cross-armed GFRP gradually degraded due to ultraviolet radiation and extreme heat, causing delamination, fiber efflorescence, and water infusion (Asyraf et al., 2022). Alkaline solutions have a more significant impact on the loss of strength in GFRP bars, and the reason for this result could be attributed to the coupled degradation actions of E-glass fibers and vinylester matrices in an alkaline environment due to hydrolysis, plasticization, and swelling (Lu et al., 2021). In this study, we manufactured rectangular GFRP samples using the manual contact molding technique, utilizing raw materials from the MAGHREB PIPE factory in the region M'sila-Algeria. We then cut the samples according to the recommended testing standards and a studied testing program.
The objective of this research to study the evolution of the mechanical and chemical properties of GFRP samples preserved in different environments over the course of one year. Additionally, to determine the durability of GFRP reinforced with Combo-Mat type glass fibers in seawater. The study also seeks to assess whether this material can be used in the future to manufacture components for maritime structures.

2 MATERIALS USED

2.1 FIBERGLASS

The reinforcements used in the PRF plates consist of a combination of a mat and a woven fabric (Combo Mat 600/300) of E-glass and a unidirectional continuous glass fiber fabric of type C. This combo mat offers high rigidity and is minimally deformable during implementation. The used C-glass fabric has a unidirectional distribution of continuous glass fibers and a surface mass of 30 g/m². The results of tests to determine the physical properties of E-glass and C-glass fibers are presented in the table below.

<table>
<thead>
<tr>
<th>Properties</th>
<th>E-glass Combo Mat</th>
<th>C-glass Fabric</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Mass (g/m²)</td>
<td>938,30</td>
<td>25,77</td>
</tr>
<tr>
<td>Moisture Content (%)</td>
<td>0,11</td>
<td>1,70</td>
</tr>
<tr>
<td>Combustible Content (%)</td>
<td>2,098</td>
<td>6,90</td>
</tr>
</tbody>
</table>

Source: Authors

2.2 RESIN

In this study, unsaturated polyester resin of the Isophthalic type (PRE-67) is used. The viscosity test results of the resin in the laboratory using the Brookfield method are presented in Table 2.
Table 2: Viscosity test results according to the Brookfield method.

<table>
<thead>
<tr>
<th>Resin mass (g)</th>
<th>Styrene mass (g)</th>
<th>Brookfield viscosity at 25°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>600</td>
<td>0</td>
<td>308</td>
</tr>
<tr>
<td>600</td>
<td>18 ou 3%</td>
<td>218</td>
</tr>
<tr>
<td>600</td>
<td>24 ou 4%</td>
<td>188</td>
</tr>
<tr>
<td>600</td>
<td>30 ou 5%</td>
<td>180</td>
</tr>
</tbody>
</table>

Source: Authors

3 PREPARATION AND PRESERVATION OF SAMPLES

The glass/polyester plates were manufactured using the manual contact molding technique. These plates have an average thickness of 7mm and were cut into rectangular shapes with dimensions of 80 x 80 cm using a diamond disc in accordance with the European standard ISO 1268-2. These plates are produced using the following raw materials: Isophthalic resin, glass fibers (a combo mat of E glass and C glass fabrics), and additives (catalysts and accelerators). The plates were manufactured by laying up five layers of combo mat and two surface layers of fabric with prepared Isophthalic resin (see Table 3) according to the European standards ISO 584 and ISO 2535.

Table 3: Results of the resin curing time test.

<table>
<thead>
<tr>
<th>Resin mass with 5% styrene (g)</th>
<th>Catalyst mass (g)</th>
<th>Accelerator mass (g)</th>
<th>Gel initiation time and temperature (min-sec)</th>
<th>Curing time and temperature (min-sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>1 ou 1%</td>
<td>0,15g ou 0,15%</td>
<td>13' à 32,50°C</td>
<td>23'38'' à 205,7°C</td>
</tr>
<tr>
<td>100</td>
<td>0,8 ou 0,8%</td>
<td>0,15g ou 0,15%</td>
<td>23'32'' à 30,40°C</td>
<td>37'38'' à 197,30°C</td>
</tr>
</tbody>
</table>

Source: Authors

The GFRP composite plates were immersed in both drinking water and seawater for 365 days at room temperature in sufficiently large tanks to allow direct contact and complete immersion of all surfaces of each plate. All manufactured plates (reference plates (R), plates immersed in drinking water (PW), and plates immersed in seawater (SW)) underwent axial tensile and three-point bending characterization. The objective was to determine the stress and strain at rupture for different immersion durations (30, 90, 180, and 365 days).
4 RESULTS AND INTERPRETATIONS

4.1 AXIAL TENSILE TEST

This test was conducted using specimens in the "I" shape with dimensions of (30X300Xe) mm³, which were kept in different environments. These specimens are placed in the testing machine (YL-25-Machine Overview), and a tensile force is applied following the ASTM D 638-03 standard.

Figure 1: Axial tensile rupture stress of GFRP specimens stored in various environments.

The axial tensile stress values of the GFRP specimens stored in different environments up to the age of 365 days are presented in Figure 1. It is clearly observed from this figure that the tensile rupture stress of the PW specimens increases significantly during the initial 90 days of storage, beyond which a decrease in stress can be observed, stabilizing in the final stage. The tensile rupture stress of the SW specimens increases up to 180 days of storage, but beyond that, we notice a decrease in stress until 365 days. The tensile rupture stress values of the SW specimens are higher than those of the PW and R specimens after 180 to 365 days of storage. The R specimens exhibit the lowest tensile rupture stress values compared to the other specimens.
The results of axial tensile rupture strain of GFRP specimens stored in different environments are depicted in Figure 2. It is evident from Figure 2 that the rupture strain of SW specimens steadily increases up to the age of 30 days, reaching a value of 8.25%. For specimens immersed in drinking water (PW), the rupture strain curve notably increases during the initial 180 days of storage, reaching its maximum value of 7.85%. However, the strain of SW samples is lower than that of R and PW specimens, with SW specimens showing regressions of 0.29% and 0.15% compared to PW and R specimens, respectively, at the age of 365 days. These results can be attributed to the diffusion effect of seawater within the immersed specimens, which subsequently leads to degradation of the material's physical properties and affects the matrix/fiber interface (Silva et al., 2014).

4.2 THREE-POINT FLEXURAL TEST

To conduct this test, GFRP specimens with dimensions of (15X160Xe) mm³ are utilized. They are positioned at the center of the testing machine (YL-25-Machine Overview), and a gradual and uninterrupted load is applied until rupture following the ASTM D 790-03 standard. Figure 3 illustrates the flexural stress curve of the GFRP samples stored in different environments. The average values of the three-point bending rupture stress are the means of five (05) values within each test series. As seen from Figure 3, the flexural rupture stress of SW specimens
increases up to 180 days of storage, where the stresses reach their maximum value (approximately 228 MPa). In fact, the flexural rupture stress of PW specimens notably increases during the initial 90 days of storage, reaching a value of 266 MPa; beyond 90 days, this stress decreases until the age of 365 days. The flexural stress of SW specimens is higher than that of R and PW specimens from 180 to 365 days. These results align with those obtained from the tensile test, and the stress reduction can be attributed to hygrothermal aging due to humidity effects, as stated by Aditya et al. [10].

![Figure 3: Flexural rupture stress of GFRP specimens stored in various environments.](source)

Figures 4 depict the flexural deformation curve of the GFRP specimens stored in various environments. It is evident from Figure 4 that the deformation of PW and SW specimens steadily increases until 90 days, but beyond this point, the deformation decreases until the age of 365 days of storage. The rupture deformation of PW specimens is higher than that of SW and R specimens after 365 days of storage. However, all tested specimens exhibit a damaged zone before complete rupture, justifying the presence of the load transfer phenomenon through the glass fibers within the material. With an increase in applied load in the critical zone, the fiber/matrix bonding can undergo significant damage, leading to fiber delamination, especially for composites stored in seawater for a duration of 365 days. Indeed, the SW composite displays minimal rupture deformation.
compared to other environments. This is likely due to the presence of salts on the surfaces and within the material, which can lead to degradation of the interface and a reduction in the properties of different components, especially with prolonged exposure duration.

Figure 4: Flexural rupture deformation of GFRP specimens stored in various environments.

![Strain at break (%) vs. Immersion time (days)](chart)

Source: Authors

4.3 SCANNING ELECTRON MICROSCOPE (SEM) OBSERVATIONS

The images observed through scanning electron microscopy (SEM) are illustrated in Figure 5. Preserving GFRP in potable water or seawater does not affect the appearance of the fiber, and no degradation is observed on the surface of the fiber filaments. The bond between the glass fibers and the matrix remains in good condition. The fibers are in good shape, and it can be stated that they are protected by the resin or that the resin acts as a sealed matrix.
5 CONCLUSION

Through this study, we can draw the following points:

- preserving GFRP plates in potable water showed a 10% increase in maximum tensile stress and a 9% gain in flexural strength at 365 days compared to control specimens;
- immersing GFRP in seawater resulted in a 14% increase in tensile strength and a 10% increase in flexural strength at 365 days compared to the control GFRP;
- the bond between the glass fibers and the GFRP matrix remains in good condition, even after being preserved for a year in a humid and sulfatic environment (seawater).

Finally, it can be said that GFRP is considered a chemically stable material, but generally, it is seldom used in the maritime field because seawater can negatively affect its mechanical properties in the long term, according to previous research. Therefore, we propose to conduct experimental studies on GFRP using other formulations or different types of resins, specifically to study the effect of sulfates on this material. Additionally, we suggest conducting numerical simulation studies on this type of material to examine its behavior.
REFERENCES


RAPPORT TECHNIQUE. Test sur les fibres de verre E et C. Laboratoire de l’usine de MAGHREB PIPE, M’sila, 2017.


TECHNICAL REPORT. Test sur les fibres de verre E et C. Laboratoire de l’usine de MAGHREB PIPE, M’sila, 2017.