

Research Article

Development and Characterization of Fiberglass/Sponge Gourd Hybrid Composites: Effect of Water Absorption on the Elastic Behavior and Impact Strength

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Abstract

Polymer matrix composites reinforced with lignocellulosic fibers have been gaining importance in various applications. However, the environment to which the composite will be exposed can significantly influence its behavior, and humid environments can be potentially aggressive. There are few studies on the microstructural characteristics and mechanical behavior of hybrid composites with sponge gourd and glass fibers, and the effect of moisture absorption and temperature on their behavior is still little explored. Therefore, in this work, aging tests were performed on glass fiber and sponge gourd fiber composites, as well as on their hybrid composite, by immersion in distilled water at two aging temperatures (25 °C and 60 °C). The mechanical behavior of aged and unaged samples was evaluated through destructive impact test and non-destructive impulse excitation test. The water absorption process was also evaluated and characterized by determining the diffusion coefficients and moisture saturation values. The impact test results allowed for the identification of failure modes and the evaluation of the effect of water absorption between the two different aging temperatures. The glass fiber composites showed little variation in impact strength before and after aging. However, the sponge gourd and hybrid composites showed considerable variation in impact strength after aging. Hybridization, however, proved efficient, and the hybrid composites exhibited impact resistance superior to that of the sponge gourd composites, even after aging. Non-destructive testing allowed for the evaluation of the aging effect on Young's modulus and loss factor. Results for the hybrid composites showed that hybridization efficiently protected the sponge gourd fibers and significantly reduced the degradation of the sponge gourd composite, in addition to providing a more environmentally friendly design alternative.

Keywords

Lignocellulosic Fibers, Aging, Hybrid Composites, Impact Strength, Water Absorption

1. Introduction

Over the last few decades, with the increase in industrial development, the demand for the development of new materials has increased, which has accelerated the research and use of composite materials in several industrial areas [1, 2]. The

most commonly used composites are those produced with a polymer matrix reinforced with synthetic fibers, such as glass and carbon fibers. However, with increased environmental awareness and reduction of resources from non-renewable

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sources, currently, resin matrix composites reinforced with lignocellulosic fibers are increasingly used, as these composites are more sustainable materials than composites using conventional synthetic fibers [1, 3-5]. Many works have discussed the advantages of using lignocellulosic fibers, highlighting their biodegradability and the fact that these fibers are obtained from natural resources [3-5]. Furthermore, polymer composites using lignocellulosic fibers usually have lower density and are more easily recycled than composites using glass or carbon fibers [6].

Several lignocellulosic fibers were analyzed both to describe their properties and to determine their suitability for use as reinforcements in polymer matrices. Sisal, jute and flax can be highlighted, for example, as widely studied fibers, and the behavior of their composites with different polymer matrices are well reported in the literature [7-12]. The behavior of several other fibers and their composites are also reported in the literature, such as composites manufactured with coir, hemp, piassava and musa fibers [13-16].

The use of lignocellulosic fibers, however, also presents disadvantages, such as greater moisture absorption and lower fiber/matrix adhesion, which can affect the mechanical properties of the composites. In fact, one of the main degradation mechanisms of polymer composites occurs due to water absorption, which can cause plasticization of the matrix, weakening of the fiber/matrix interface, which can lead to the formation of cracks and/or voids, in addition to increasing the weight of the material. For example, Srihari et al. [17] showed that polymer composites reinforced with glass fiber present considerable loss of mechanical properties due to water absorption. Espert et al. [18] showed that the mechanical properties of composites reinforced with lignocellulosic fibers are greatly influenced by exposure to humidity. In other words, the effects due to moisture absorption cause chemical, mechanical and thermophysical changes in polymer matrix composites, both those reinforced by lignocellulosic fibers and those reinforced by synthetic fibers [17-23].

The process of degradation of polymer composites by water absorption initially occurs through the penetration of water through the matrix and/or fiber/matrix interfaces [19, 24]. Soon after, cracks may appear in the matrix and, thus, the composite will absorb more and more water more rapidly, causing a loss of its mechanical properties [17, 24]. Although in some cases the water absorption process in composites may occur in an anomalous, or non-Fickian, manner [23, 25, 26], the Fick model can effectively describe the diffusion process in many fiber-reinforced composites, including lignocellulosic fiber-reinforced composites [20, 23, 27, 28].

One of the strategies to minimize the problem of water absorption in composites with lignocellulosic fibers is the use of hybrid composites, with lignocellulosic and synthetic fibers [29, 30]. Typically, since lignocellulosic fibers absorb more water, hybrids are manufactured using synthetic fibers on the surface and lignocellulosic fibers in the interior of the composites [31, 32].

Therefore, the objective of this work was to evaluate the effect of aging by immersion in distilled water on the mechanical behavior of a hybrid epoxy matrix composite reinforced by glass and sponge gourd (*Luffa cylindrica*) fibers and to compare the effect of hybridization in relation to behavior of composites with only glass fiber or sponge gourd fiber. The sponge gourd fiber was chosen because it forms a natural three-dimensional network, which can allow the development of composites with increased tenacity, even with brittle matrices, such as cementitious ones [33]. The evolution of the degradation process was analyzed by determining the water absorption kinetics in the composites and evaluating the variation in the elastic modulus and damping factor by non-destructive sound testing. The variation in mechanical behavior was evaluated by destructive impact testing. Since temperature has a great influence on the entire degradation process of polymer composites by water absorption, as increasing the temperature accelerates the absorption process and can accelerate degradation in the composite [34, 35], the composites were aged in distilled water at 25 °C and 60 °C.

2. Materials and Experimental Methods

To manufacture the composites, a two-component epoxy resin was used, employing a resin/hardener ratio of 100/25 parts by weight. Three types of epoxy matrix composites were manufactured by manual lamination, namely: i) Composite A - reinforced with glass fibers, using 20 layers of a bidirectional (0/90) glass fiber fabric, so that the laminate produced had 50% of glass fibers oriented at 0° and 50% oriented at 90°; ii) Composite B - reinforced with sponge gourd fibers, using 4 layers of the natural sponge blanket (Figure 1), which forms a three-dimensional fiber fabric; iii) Composite C - hybrid composite with glass and sponge gourd fibers, using 10 layers of glass fiber fabric and 2 layers of the natural sponge blanket. The glass fibers were placed on the outer surfaces of the composite laminate, forming a sandwich-type laminate with the following stacking sequence: 5 layers of glass fiber/2 layers of sponge fiber/5 layers of glass fiber. With this manufacturing strategy, composites with approximately 35-40% fiber volume fraction were produced.



Figure 1. *Sponge gourd blanket used to manufacture the sponge gourd and hybrid composites.*

After lamination, and to control the thickness of the laminates manufactured, the laminates were placed in a mold covered with high-density polyethylene, which served as a release agent. The mold was then closed and placed in a hydraulic press under a pressure of 4 tons, being kept under this pressure for 24 hours.

Rectangular specimens measuring 120 mm long, 20 mm wide and, on average, 6 mm thick were machined from the laminates obtained. These samples were aged in distilled water at 25 °C and 60 °C, for a total of ~4 months (122 days). During this period, samples were regularly weighed to measure water absorption in the composites. This test was carried out in accordance with the ASTM D 570 standard [36]. The measurements were made using an analytical balance with an accuracy of ± 0.001 mg. In each weighing, the samples were dried uniformly so that there would be no interference in the absorption results. The specimens were considered saturated when the mass variation (M%) between two consecutive measurements was less than 1%.

At two predetermined times, based on the analysis of the absorption curves, namely at 1863 h and 2928 h, during the removal of samples to measure water absorption, the samples were subjected to non-destructive impulse excitation test to measure the variation in the modulus of elasticity and also in the damping factor. The elastic modulus, indicative of the stiffness and deformation capacity in the elastic regime, directly influences the correct application of each type of composite. Furthermore, it is a relevant parameter when evaluating materials aged in water, where its stabilization may indicate a stabilization of water damage [37]. The other parameter determined by this technique, the damping factor, is related to the energy dissipation mechanisms and the internal friction of the material. This parameter is also important for understanding the progressive damage of the composite over time, being a significant indicator of degradation [38, 39].

Figure 2 shows the arrangement of the microphone and actuator for the impulse excitation test in the flexural sound ex-

citation mode. The specimens were tested using the Sonelastic® equipment (ATCP) and each test consists of data collected from 40 actuator impacts, with a 30-second interval between them. Three samples were tested per aging temperature. The acoustic response is transformed into a digital signal and sent to a computer that identifies the natural frequencies and calculates the modulus of elasticity. The damping coefficient is calculated from the sound attenuation rate.

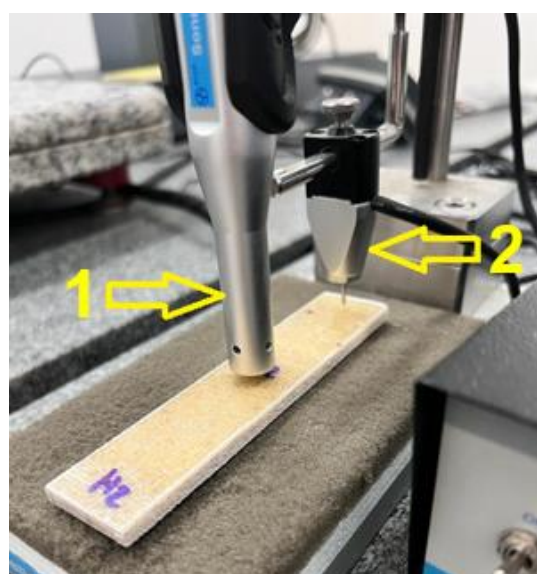


Figure 2. *Non-destructive impulse excitation test. Microphone (1) and actuator (2) positioned on the test piece.*

The impact tests were performed based on the ISO 179-1:2023 standard [40]. The tests were performed on a CSI model 137D instrument, using a Charpy pendulum configuration with a rounded tip, on unnotched specimens. A span of 90 mm was used and the specimens were positioned flatwise, i. e., with the specimen thickness perpendicular to the impact blow. The initial impact energy of the pendulum was 5.7 J, and the test was performed on 9 samples of each composite type, before and after an aging period of 4 months.

3. Results and Discussion

3.1. Water Absorption

The main objective of the absorption test was to obtain the mass gain curve over time to determine the diffusion coefficient of the composites. Figure 3 shows, as an example, the typical graph obtained for all analyzed composites (i. e., glass fiber, sponge gourd fiber and hybrids), both at room temperature and at 60 °C. An increase in mass was observed with an initial linear region, followed by a plateau that tends towards the saturation value, corroborating the behavior described in the literature [20, 23, 28].

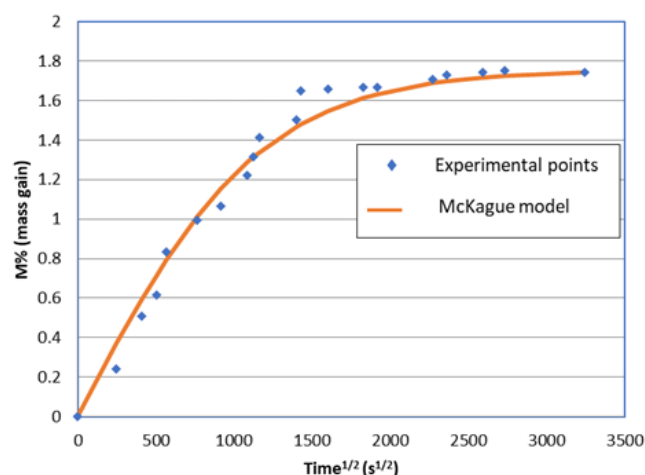


Figure 3. Mass gain (%) vs. square root of time ($s^{1/2}$) of a sample of glass fiber composite aged at room temperature. The McKague model [41] was used to fit the experimental data.

The experimental points were adjusted using the equation proposed by McKague et al [41] which describes the absorption process for both short and long times, namely:

$$\frac{M_t}{M_\infty} = \frac{4}{h} \left(\frac{Dt}{\pi} \right)^{1/2} \quad (1)$$

where M_t is the amount of water absorbed at time t ; M_∞ is the value absorbed at saturation; h is the sample thickness and D is the diffusion coefficient. The value of M_t is determined from the relationship between the mass of the sample at time t and the mass of the dry sample, i. e.,

$$M_t, \% = \frac{w_i - w_0}{w_0} \times 100 \quad (2)$$

where w_i is the updated value of the sample mass at time i and w_0 is the initial value of the sample mass.

The average results obtained for the diffusion coefficient (D) and the saturation value (M_∞) for all composites are listed in Table 1. Table 1 also lists the range of correlation coefficients (r^2) obtained for all samples of each type of composite, fitting the experimental data to the McKague model equation. It is possible to observe, from the values of the correlation coefficients obtained, that the experimental points fit the model well. In fact, correlation coefficient values greater than 0.90 indicate a very strong correlation between the experimental data and the model used [42].

Table 1. Absorption parameters adjusted for the composites.

T = 25 °C			
Composite	M_∞ (%)	D ($10^{-6}\text{mm}^2/\text{s}$)	r^2
Glass fiber	1.76 ± 0.18	0.91 ± 0.16	0.960 - 0.984
Luffa fiber	20.60 ± 2.60	3.12 ± 0.61	0.973 - 0.987
Hybrid	12.57 ± 0.91	1.47 ± 0.37	0.974 - 0.981
T = 60 °C			
Composite	M_∞ (%)	D ($10^{-6}\text{mm}^2/\text{s}$)	r^2
Glass fiber	1.19 ± 0.17	1.72 ± 0.38	0.967 - 0.980
Luffa fiber	19.22 ± 1.09	10.33 ± 3.81	0.991 - 0.995
Hybrid	15.02 ± 1.62	2.99 ± 0.63	0.980 - 0.985

For the composite reinforced by glass fibers, the adjusted values for the diffusion coefficient (D) and the saturation value (M_∞) are consistent with the values reported in the literature for tests at room temperature. Values ranging from $0.15 \times 10^{-6}\text{mm}^2/\text{s}$ to $6.63 \times 10^{-6}\text{mm}^2/\text{s}$ are reported for the diffusion coefficient [23, 43-46].

The same can be said regarding the saturation absorption value, M_∞ . Several studies on absorption in distilled water at

room temperature of polymer composites reinforced with glass fibers showed absorption values between 0.42% and 2.00% [43-47]. According to the literature, the average time for saturation of fiberglass composites occurs between 2 and 3 months [48]. It can be seen in Figure 3 that the composite begins to stabilize its mass gain after 1863 hours ($2590 s^{1/2}$), that is, 2.5 months.

As expected, the absorption values of the sponge gourd

composite were much higher than that of glass fiber (Table 1). In fact, composites made with lignocellulosic fibers have a notable tendency to absorb large amounts of water, as cellulose based fibers are highly hydrophilic [3, 6, 17, 21, 27]. Previous work on absorption in distilled water at room temperature of polymeric composites reinforced with sponge gourd fiber show maximum absorption values (M_{∞}) between 12% and 25% and diffusion coefficient (D) between $2.0 \times 10^{-6} \text{ mm}^2/\text{s}$ to $21.0 \times 10^{-6} \text{ mm}^2/\text{s}$, being consistent with the values found in this work [20, 37, 49].

Studies that analyze the absorption of distilled water at room temperature in hybrid polymeric composites (glass fiber/lignocellulosic fiber) present maximum absorption values between 4.4% and 22.0% [50-54]. It should be noted that several factors can affect this value, such as the type of fiber used, the glass fiber/lignocellulosic fiber ratio and also the total volume fraction of fibers in the composite. However, it is possible

to compare the order of magnitude of the values obtained with those reported in the literature and, as shown in Table 1, the results obtained are in agreement with the literature data.

Figure 4 shows the comparison between the three types of composites. The plotted curves represent the average of the experimental absorption results for each composite. It is possible to observe that the hybrid composite mitigates water absorption in relation to the composite with only sponge gourd fiber, which was expected and agrees with literature data [50-54]. This behavior may cause less swelling of hybrid composites due to water absorption, compared to sponge gourd composites and, therefore, increases the dimensional stability of these hybrid composites. Indeed, in several applications of composites with lignocellulosic fibers, such as panels, dimensional stability is a relevant factor.

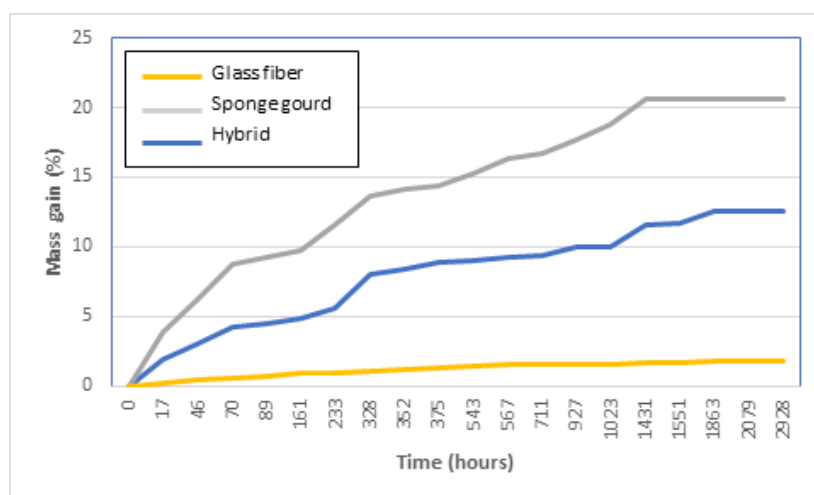


Figure 4. Comparison of the mass gain vs. absorption time at room temperature for glass fiber, sponge gourd and hybrid composites.

In relation to glass fiber composites aged at 60 °C, the values for the diffusion coefficient (D) and maximum absorption (M_{∞}) values, presented in Table 1, are also consistent with the values reported in the literature. Several studies on absorption in distilled water at high temperature of polymer composites reinforced with glass fibers showed absorption values between 0.42% and 1.5% [44, 46]. However, some studies reported absorption of up to 3% [55]. Factors such as the type of polymer matrix, the fiber fraction, and fiber alignment can cause this difference in values reported in the literature, as can the aging temperature used.

Comparing the results between 25 °C and 60 °C, it is observed that the diffusion coefficient increases with increasing temperature, which was expected considering that the diffusion coefficient is dependent on temperature, following the Arrhenius model. The reduction in the saturation value can be linked exactly to a possible post-curing of the composite. In fact, post-curing results in an increase in the cross-link density of the polymer matrix, which results in a reduction in the water

saturation value, as observed in several works [56, 57].

As shown in Table 1, the same behavior of increasing the diffusion coefficient with increasing temperature was observed for the sponge gourd composite. However, there was no variation in relation to the saturation value. This result is consistent with the fact that fibers are the main element for diffusion in this composite due to their hydrophilic character. Thus, the contribution of the matrix is minimized and any post-curing effect that may be occurring in the polymeric matrix has a secondary contribution to the water diffusion/absorption process.

For the hybrid composite, there was also an increase in the diffusion coefficient, as expected, but, different from what was observed for composites with only one type of fiber, there was also an increase in the absorption value at saturation. The hypothesis raised here is that, due to the difference in expansion coefficients caused by the hydrothermal effect between the glass fiber and sponge gourd fibers layers, cracks were generated at the interfaces between these layers, allowing for

greater water absorption. The observation of failures due to delamination in the hybrid composites will be demonstrated in the analysis of impact tests.

Figure 5 shows a comparison of the absorption curves between the three types of composites aged at 60 °C. Again, the curves presented represent the average values of the absorption results for each composite. This result is similar to that

observed for absorption at room temperature (Figure 4) and indicates that the presence of glass fiber layers can significantly influence water absorption in the hybrid composite, creating a barrier effect that makes water penetration more difficult, even at higher temperatures.

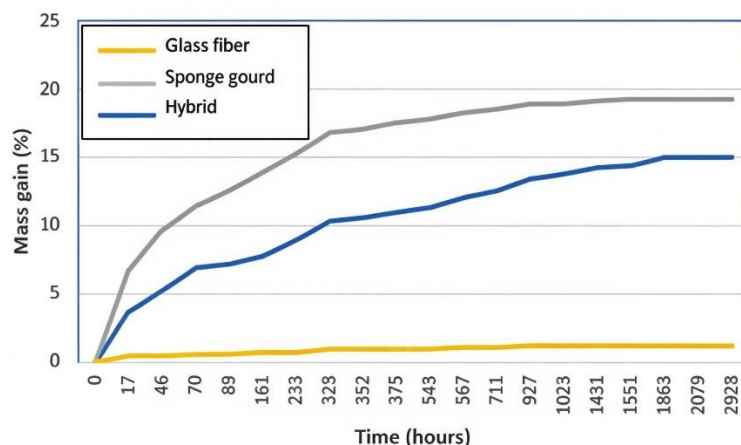


Figure 5. Comparison of the mass gain vs. absorption time at 60 °C for glass fiber, sponge gourd and hybrid composites.

3.2. Impact Test

The results of the Charpy impact test of the unaged compo-

sites are shown in Figure 6. The glass fiber reinforced composite showed greater impact resistance, as expected. It is also observed that hybridization caused an increase of approximately 380% in the value of impact energy in relation to the sponge gourd composite.

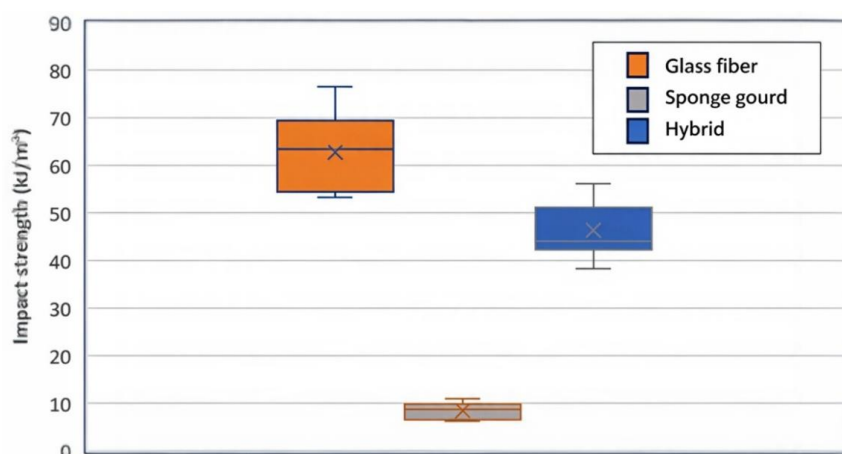


Figure 6. Impact strength of unaged glass, sponge gourd and hybrid composites.

The experimental data obtained were statistically analyzed. Initially, the normality of the data for each composite was tested using the Shapiro-Wilk test. The normality of the data was confirmed with a significance level of 5% ($p > 0.05$). Next, an analysis of variance (ANOVA) was performed to test the

differences in values between the groups. A statistically significant difference was observed between the materials in relation to their impact resistance ($F=207.3$; $DF=26$; $p<0.01$). Finally, the Tukey test was used to identify which groups differed from each other with respect to the variable tested. In all analyses, a significance level of 5% was considered, and, as

can be inferred from the box plot shown in Figure 5, all means present a statistically significant difference from each other ($p < 0.01$).

The glass fiber composites did not show complete rupture, as shown in Figure 7a. The formation of a whitening zone was observed, which is associated with the development of microcracks in the resin [58] or rupture of the fiber-matrix interface [59]. This mechanism is commonly reported for glass fiber composites under static [60] or dynamic [61] bending

loading. The hybrid composites also did not show complete rupture and there was the formation of an incipient whitening zone (Figure 7b). In other words, hybridization was efficient in terms of increasing the amount of energy absorbed upon impact and also in altering the failure mode of the composite. This is because, as shown in Figure 7c, the sponge gourd composites failed with complete rupture.

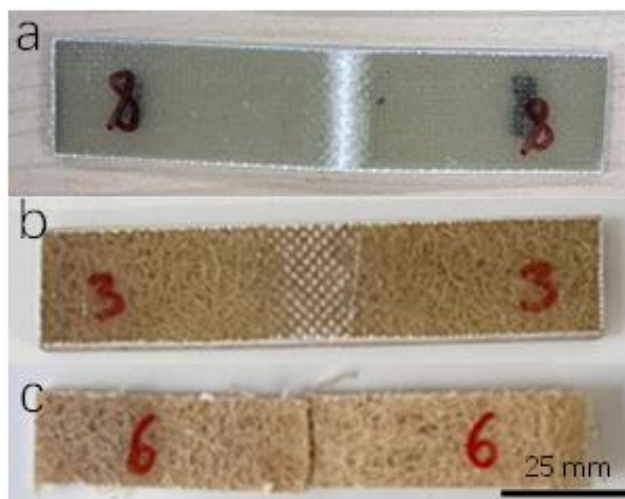


Figure 7. Example of the failure mode of the unaged test specimens submitted to the Charpy impact test.

The results of the three types of composites aged at room temperature are presented in Figure 8. It is observed that the hybrid composite presented an important reduction in its impact behavior, because after aging, compared to the sponge

gourd composite, there was an increase in impact strength of only 34.8%, compared to 380% of the material without aging.

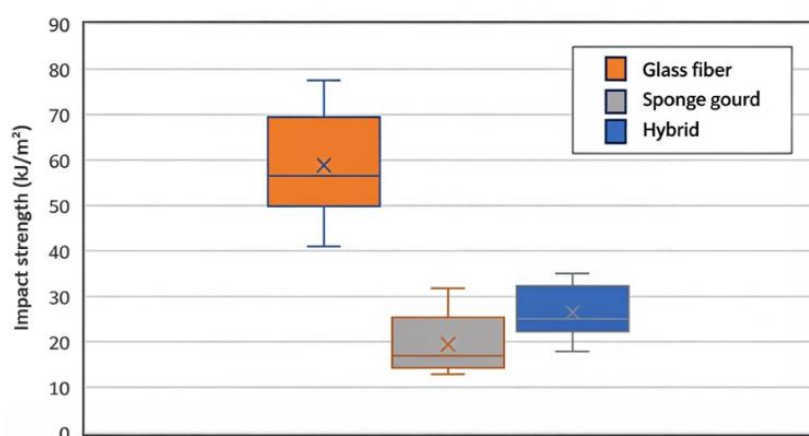


Figure 8. Impact strength of glass, sponge gourd and hybrid composites aged at room temperature.

The same statistical analysis procedure was performed for these samples. The normality of the data was confirmed (Shapiro-Wilk test, $p > 0.05$) and it was observed that there was

a statistically significant difference between the results. However, the Tukey test, considering a significance level of 5%, shows that there is no statistically significant difference between the sponge gourd and hybrid composites, as could have

been anticipated by the box-plot shown in Figure 8.

Regarding the failure mode, none of the composites exhibited total failure. For the glass fiber composites, a wider whitening region was observed compared to that of the unaged composite, Figure 9a. This may indicate a higher percentage of interfacial failures, which agrees with the effect of water absorption in polymer composites [62]. The same behavior was observed for hybrid composites (Figure 9b).

It is important to note, as shown in Figure 9c, that the aged sponge gourd composites did not fail, unlike what was observed for the unaged composite (Figure 7c). The samples

showed permanent deformation, with the fibers joining the two halves of the specimens. This behavior may be associated with the plasticization effect of the polymer matrix, due to water absorption by the fibers, which increases the tenacity of the composite [62, 63]. In fact, as shown in Figure 10, some samples showed delamination, indicating that water absorption may have caused phenomena such as swelling/rupture of interfaces and led to a greater energy absorption capacity for these composites.

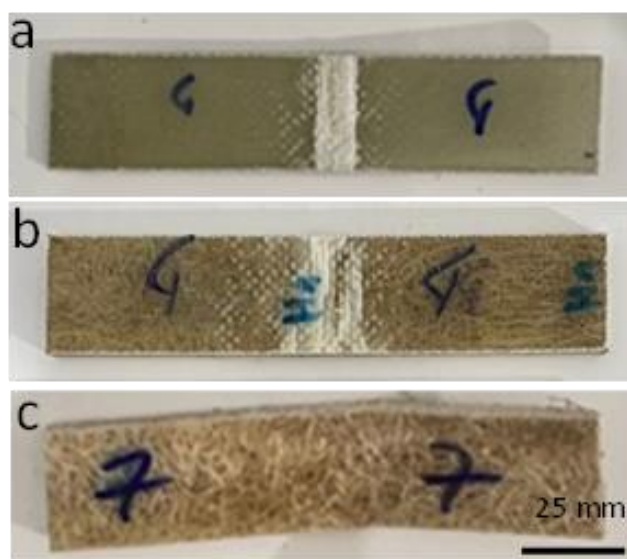


Figure 9. Example of the failure mode of test specimens submitted to the Charpy impact test after aging at room temperature.

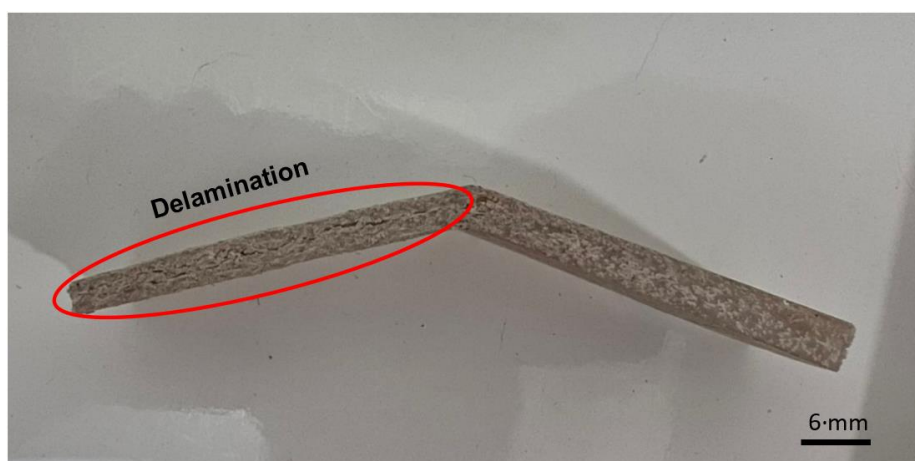


Figure 10. Sample of sponge gourd composite aged at room temperature showing a delamination crack running along its side.

The results of the composites aged at 60 °C are shown in Figure 11. As expected, the hybrid composite presents an impact resistance value lower than the glass fiber composite, but higher than that of sponge gourd. Statistical analysis of the data indicated that the normality of the data was not confirmed

due to the presence of an outlier in the sponge gourd composite. Therefore, the Kruskal-Wallis analysis was performed to test the differences between the groups in relation to impact resistance and a statistically significant difference was observed between the materials ($H=23.14$; $p<0.01$).

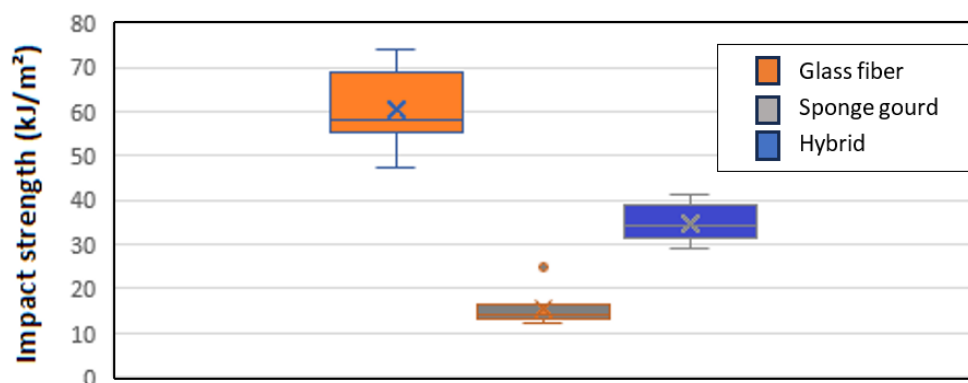


Figure 11. Impact strength of glass, sponge gourd and hybrid composites aged at 60 °C.

None of the composites showed total rupture, similar to what was observed for aging at room temperature. In the hybrid composites, delamination was observed along the entire length of several specimens, [Figure 12](#), before the test. Delamination was not observed in the hybrid composites—either

unaged or aged at room temperature. This corroborates the hypothesis that, due to water absorption and the difference in hygrothermal behavior between glass fibers and sponge gourd fibers, cracks form during aging.



Figure 12. Hybrid composites aged at 60 °C showing cracks running along the entire side of the specimens.

[Figure 13](#) shows the variation in impact resistance of each type of composite as a function of aging condition. It can be observed that, for the glass fiber composite, there was no statistically significant variation in impact resistance. For the sponge gourd composite, the impact resistance showed a small increase due to aging. This behavior was associated with possible plasticization of the composite matrix induced by water absorption, as already discussed. In fact, the unaged composites broke into two parts after the impact ([Figure 7c](#)), while in the aged composites there was no rupture of the specimens, indicating greater toughness ([Figure 9c](#)). The impact resistance of the hybrid composite decreases for both aging conditions, reducing the efficiency of this composite in relation to the sponge gourd composite. As manufactured, the hybrid composite exhibited an average impact resistance 4.8 times

greater than that of sponge gourd, but this value drops to less than 2.5 in aged composites.

3.3. Impulse Excitation Test

The non-destructive impulse excitation test was performed on the samples as manufactured and also after 1863 and 2928 hours of immersion, both at 25 °C and 60 °C. For glass fiber composites ([Figure 14](#)), it is observed that there is no statistically significant variation in the elastic modulus for samples aged at 25 °C. However, for composites aged at 60 °C there was a reduction in values. These results corroborate the qualitative analysis of the failure mode of the composites in the impact test which showed a steadily increase in the whitening region with temperature ([Figure 7a vs. 9a](#)).

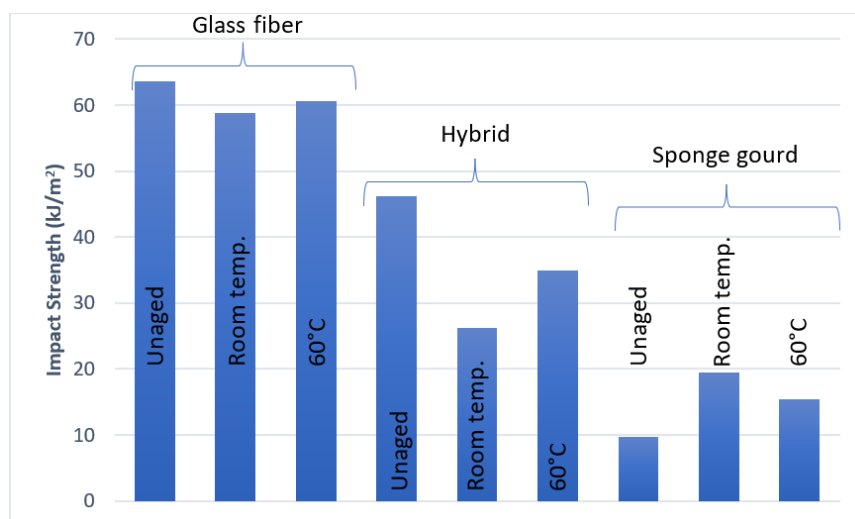


Figure 13. Variation of the impact strength as a function of the aging temperature.

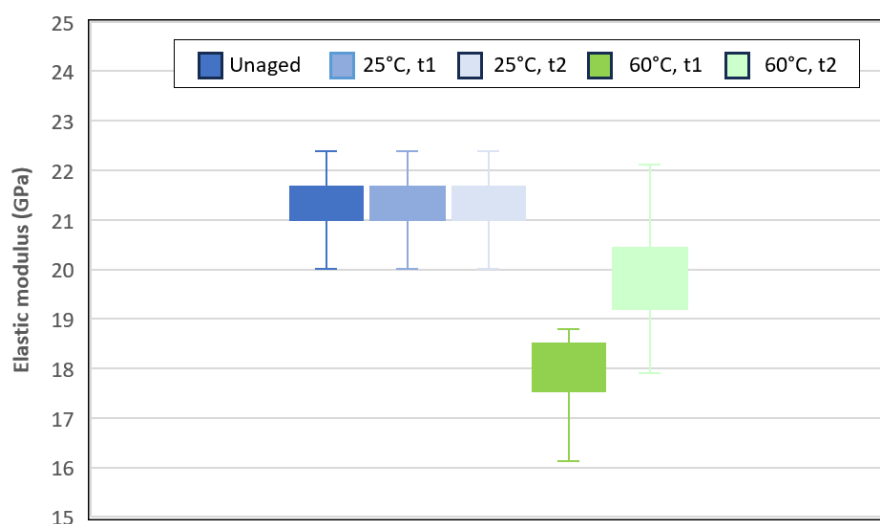


Figure 14. Variation of the elastic modulus of fiberglass composites aged at 25 °C and 60 °C. Aging times: $t_1 = 1,863$ h; $t_2 = 2,928$ h.

Damage mechanisms associated with whitening may be responsible for the observed reduction in values [58, 59]. It is also observed that the composite subjected to the highest temperature (60 °C) and tested during the longest absorption time (2,928 h) was the one that presented the greatest dispersion of experimental data, which may indicate that the combined effect of temperature and immersion time is leading to changes in the structure of the composite. In fact, comparing the results at immersion times of 1,863 h and 2,928 hours for samples aged at 60 °C, an apparent recovery of the modulus is observed with increasing time. A possible explanation for this fact is that, with increasing time that the composite remains submerged in water, matrix swelling may occur [64], causing an increase in interfacial stresses and, consequently, increasing the stiffness of the material due to better stress transfer at the

fiber/matrix interface [65, 66].

The evolution of the loss factor appears to be more sensitive to the effects of aging than the elastic modulus. In fact, while the modulus depends mainly on the fibers, damping depends on the defects that can be generated in the material. Thus, even at 25 °C, an increase in the loss factor was observed for the longer aging time compared to the unaged material. For aging at 60 °C, the observed behavior followed the same trend as the elastic modulus. For the first aging time, a statistically significant drop in the average value (76.6%) is observed, but after 2,920 hours of aging, the average value is not statistically different from the value of the material without aging, Figure 15. It should be noted, once again, that there was a large increase in the standard deviation, possibly indicating greater heterogeneity in the material due to the effects of aging.

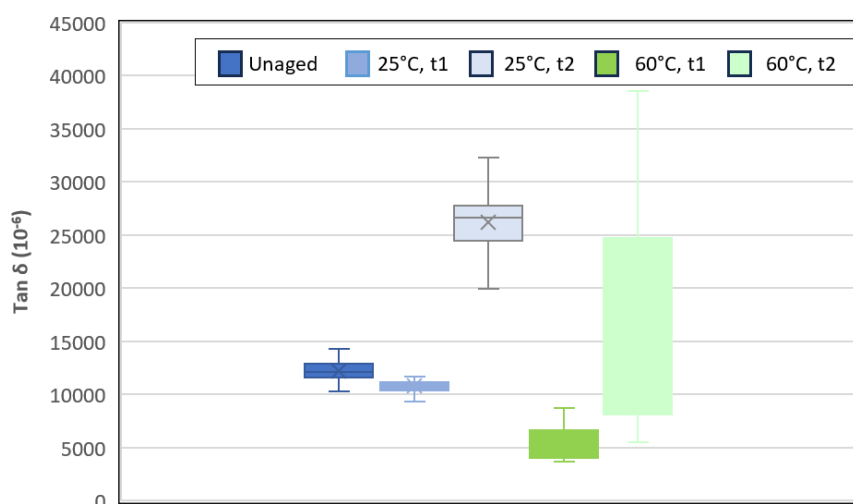


Figure 15. Variation of the damping factor of fiberglass composites aged at 25 °C and 60 °C. Aging times: $t_1 = 1,863$ h; $t_2 = 2,928$ h.

Good interaction, with good adhesion, between the fibers and the matrix, and defect-free interfaces, would result in less variation in the damping factor when comparing the values before and after water absorption. Weak adhesion between the fibers and the matrix, as well as the presence of defects at the interface, which could possibly be filled with water and could cause swelling of the matrix, would lead to greater variation in damping. It would be expected, then, that when the amount of water absorbed is sufficient to reduce interfacial adhesion, there should be an increase in damping compared to the value

measured before aging [64].

As could be predicted from the impact and absorption test results, the higher water absorption by the sponge gourd fibers resulted in a significant reduction in the elastic modulus values compared to the unaged sponge gourd composite, Figure 16. As shown in Figure 16, there is no statistically significant difference between the values after 1,863 and 2,928 hours of immersion in water at 25 °C, nor after 1,863 hours of aging at 60 °C. For composites aged for 2,928 hours at 60 °C there was a greater drop in modulus (approximately 50%).

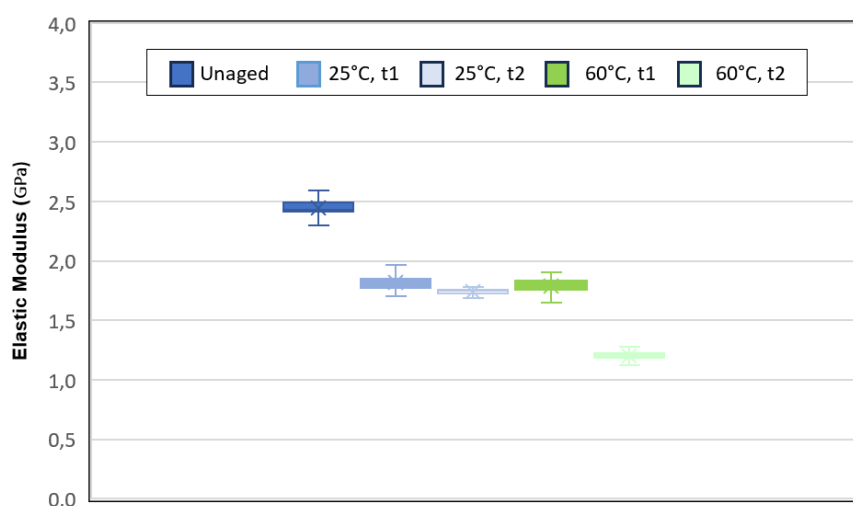


Figure 16. Variation of the elastic modulus of sponge gourd composites aged at 25 °C and 60 °C. Aging times: $t_1 = 1,863$ h; $t_2 = 2,928$ h.

In general, at both aging temperatures, an increase in damping was observed, suggesting that, as can be seen in Figure 17, aging caused plasticization of the matrix and degradation of the fiber/matrix interfaces, resulting in increased damping. The large dispersion of results is also evident, which may indicate a lack of homogeneity in the degradation process. It is

important to remember here that the experimental result represents the average of 120 measurements, so the increase in variability actually indicates a heterogeneous response from the material.

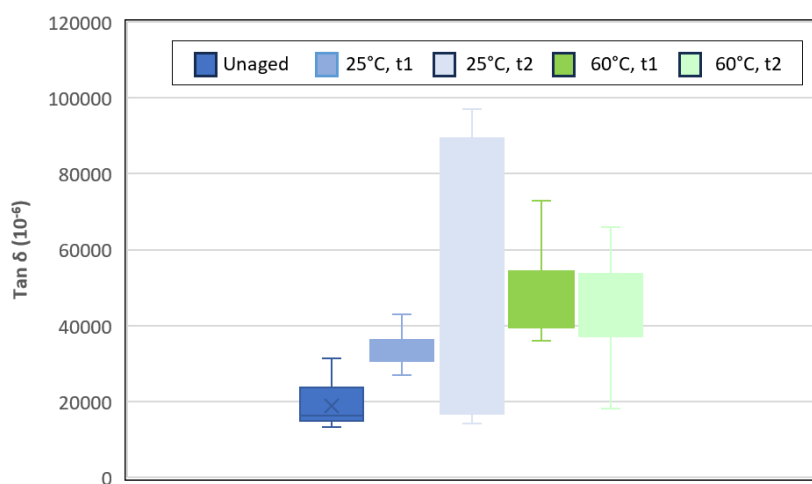


Figure 17. Variation of the damping factor of sponge gourd composites aged at 25 °C and 60 °C. Aging times: $t_1 = 1,863$ h; $t_2 = 2,928$ h.

The results for the hybrid composite (Figure 18) showed that hybridization was effective in stabilizing the elastic modulus of the composite, both during aging at 25 °C and at 60 °C. For composites aged at 25 °C, the experimental values ob-

tained are not statistically different from each other or in relation to the unaged material. This behavior was similar to that observed for glass fiber composites (Figure 14) and indicates that the placement of glass fibers on the surface of the composites efficiently protected the sponge gourd fibers.

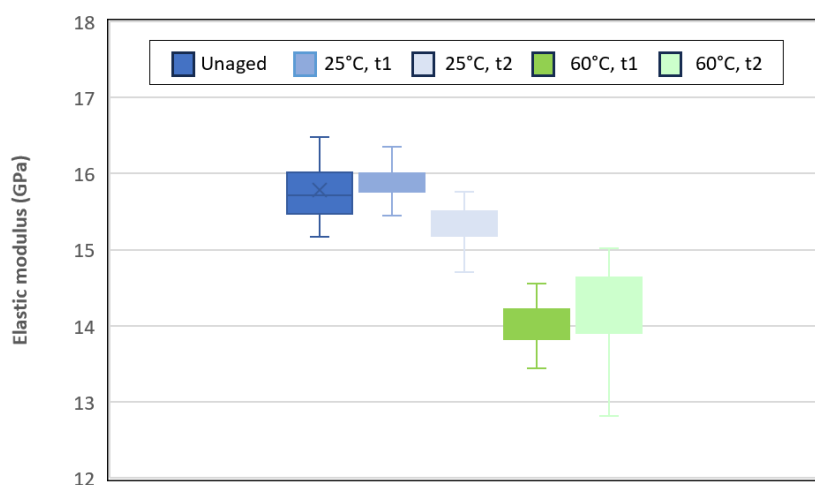


Figure 18. Variation of the elastic modulus of hybrid composites aged at 25 °C and 60 °C. Aging times: $t_1 = 1,863$ h; $t_2 = 2,928$ h.

For composites aged at 60 °C, there was an initial drop of 7.7% after 1,863 hours of immersion, but the modulus value stabilized between immersion times. In other words, the sponge gourd fibers were again protected by the presence of outer layers of glass fibers. It should be noted that, at 60 °C, the sponge gourd composite underwent significant degradation (Figure 16), which did not occur when hybridization took place.

The damping variation for the hybrid composite specimens before and after aging is shown in Figure 19. Two characteristics can be highlighted. As already observed in other graphs

related to damping, there is a large dispersion of the data, leading to high standard deviations. And, most importantly, it can be observed that there is no statistical variation between the results, both at 25 °C and 60 °C. In other words, although there is a tendency for the average value to increase, especially at 60 °C, the damping value, which is associated with the evolution of damage to the material, remained constant, corroborating that hybridization acted efficiently in protecting the sponge gourd fibers.

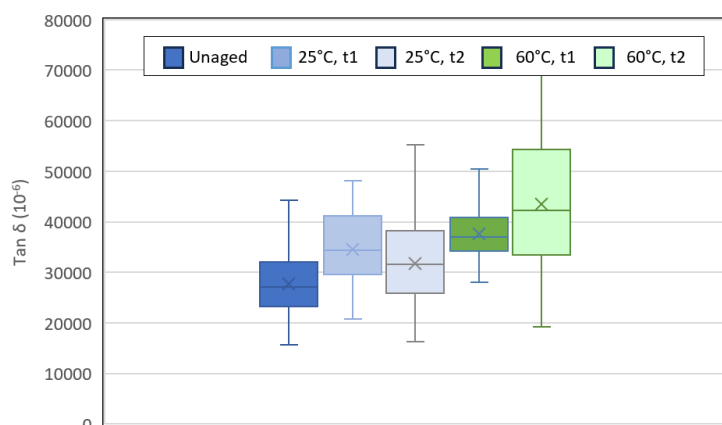


Figure 19. Variation of the damping factor of hybrid composites aged at 25 °C and 60 °C. Aging times: $t_1 = 1,863$ h; $t_2 = 2,928$ h.

4. Conclusions

The results obtained in this work showed that the hybridization of glass fiber with sponge gourd fibers was efficient. Hybridization significantly reduced the degradation of the hybrid composite compared to that of the sponge gourd composite when exposed to humid environments, in addition to providing a more environmentally friendly design alternative by replacing part of the glass fibers. In fact, the use of outer layers of glass fiber sandwiching the sponge gourd fibers reduced the amount of absorbed water, even considering that the test samples used had unprotected sides.

In terms of impact resistance, the unaged hybrid composites showed approximately 380% greater impact resistance than the sponge gourd composite, and hybridization proved efficient in preventing sample rupture. Aging, however, caused a significant loss of impact resistance in the hybrid composites. This behavior was attributed to water absorption by the fibers, which need to be isolated from the external environment when used in practical applications.

Non-destructive testing showed that temperature was more important in terms of degradation of sponge gourd composites and hybrids than immersion time. Therefore, the Young's modulus was reduced for all composites, including glass fiber composites.

Abbreviations

DF Degree of Freedom

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Author Contributions

Ronaldo Gomes de Castro Medeiros: Data curation, Investigation, Methodology, Validation, Writing – original draft

José Roberto Moraes d'Almeida: Conceptualization, Investigation, Resources, Supervision, Writing – review & editing

Conflicts of Interest

The authors declare no conflicts of interest.

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