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Mechanical and Hygroscopic Characteristics of Unidirectional Jute/Glass and Jute/Carbon Hybrid Laminates

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ABSTRACT

Physical and mechanical performance of natural fiber composites can be tailored by hybridizing with synthetic fibers. Jute fibers are promising and highly available at a low cost in some countries, and they have been used in several applications, with the extra benefit of helping socially depressed people who commonly explore this plant. This work investigates the effect of hybridization on the properties of jute/glass and jute/carbon laminates with polyester resin. Nine different laminates were manufactured by vacuum infusion using unidirectional jute, E-glass, and carbon fabric reinforcements. Tensile, flexural, and short beam tests were performed in accordance with ASTM standards. The hybrid composites showed generally intermediate properties compared to the non-hybrid two-component laminates. The mechanical properties of the hybrid composites were 50–75% smaller than those of their respective pure glass and pure carbon composites, but 30–300% higher compared to the pure jute composite. Among the hybrids, the number of layers of the synthetic fiber played the most important role on properties, rather than the layup. That is, the variation in the number of jute fabrics may produce the required combination of stiffness and strength for different applications. Besides, the hybrid laminates, with more layers of synthetic fibers showed better hygroscopic performance.

摘要

天然纤维复合材料的物理和机械性能可以通过与合成纤维杂交来定制. 黄麻纤维在一些国家很有前途, 而且价格低廉, 而且很容易获得, 它们已被用于多种应用中, 有助于帮助那些经常探索这种植物的社会抑郁症患者. 本文研究了杂化对聚酯树脂黄麻/玻璃和黄麻/碳层压板财产的影响. 使用单向黄麻、E-玻璃和碳纤维增强材料通过真空浸渍制备了九种不同的层压板. 根据ASTM标准进行拉伸、弯曲和短梁试验. 与非混杂双组分层压板相比, 混杂复合材料通常表现出中等的财产. 混杂复合材料的力学财产比各自的纯玻璃和纯碳复合材料小50-75%, 但比纯黄麻复合材料高30-300%. 在这些杂种中, 合成纤维的层数对财产起着最重要的作用, 而不是铺层. 也就是说, 黄麻织物数量的变化可能会产生不同应用所需的硬度和强度组合. 此外, 具有更多层合成纤维的混合层压板显示出更好的吸湿性能.

KEYWORDS
Hybrid composites; natural fibers; unidirectional laminates; vacuum infusion; mechanical properties

关键词
混杂复合材料; 天然纤维; 单向层压板; 真空输注; 机械财产

Introduction

Jute is a natural plant originally from Asia but genetically adapted to grow in the humid soils of Northern Brazil, especially on slopes at both the Amazon and Solimões rivers, where these plantations cover about 15 cities. The whole production chain in Brazil employs about 20 thousand workers and the main jute end-products include yarns, fabrics and bags, especially for packing coffee. New

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applications capable of increasing the value of jute fibers could clearly favor socially depressed people who explore this plant in different countries.

Like other natural fibers, jute fibers are advantageous over synthetic ones, especially glass, due to good specific mechanical properties, high flexibility, renewability, recyclability, biodegradability, low toxicity, neutral carbon footprint and low thermal and acoustic conductivities (Farhan et al. 2021; Latif et al. 2019). Indeed, the advantages of natural fibers in composites have been successfully exploited in different sectors, including naval, automobile and civil construction (Angrizani et al. 2017; Kumar, Arul Marcel, and Selwin Rajadurai 2021).

Natural fiber-reinforced composites also have the potential of replacing hardwoods in musical instruments. Currently, forests with high-quality woods, such as those required for instruments, have been consumed by intense extractive activities, with consequent increase in cost and decrease in availability. Compared to wood, composites based on natural fibers have similar aesthetic attributes, in addition to greater resistance against aging in critical hygrothermal conditions and tailorable properties. On that context, recent studies have reported potential advantages related to functionality, sound and cost of fibrous composite instruments (Abu Hena Md et al. 2022; Ahmed and Adamopoulos 2018).

In hybrid composites where different fibers are simultaneously used, natural fibers may also be advantageous, bringing different characteristics to the final products. Although many combinations of natural fibers have been studied (Arulmurugan et al. 2020; Siakeng et al. 2020), synthetic fibers are incomparable in solving known deficiencies of plant fibers, such as seasonality, limited mechanical properties, high water absorption and low chemical affinity with hydrophobic polymeric matrices (Sivakandhan et al. 2020; Yasir et al. 2021).

For instance, a recent study evaluated the dynamic-mechanical, thermal, crystallinity, and chemical properties of rice husk and coco peat-reinforced acrylonitrile-butadiene-styrene hybrid composites, reporting that a rice husk/coco peat weight ratio of 15/5 enabled the substitution of the synthetic matrix with an acceptable level of characteristics, especially useful for damping applications (Haris, Hassan, and Ilyas 2022). Jagadeesh et al. (2022) investigated carbon woven fabrics hybridized with areca and sisal woven fabrics. A poly-amine hardened epoxy resin was used and the composites were manufactured by hand-layup. They concluded that the carbon reinforcements were the main responsible for tensile strength and modulus, and that bending and interlaminar shear properties were mostly dependent on the stacking sequence, especially the outside layers. In another study, bidirectional reinforced polyester composites with variable jute (*c.a.* 2.5–7.5%) and carbon (*c.a.* 7.5–22.5%) fiber fractions were investigated (Ravikumar, Suresh, and Rajeshkumar 2022). Also, chemically modified kenaf-epoxy composites were hybridized with multi-walled carbon nanotubes (MWCNT) incorporated into the resin by high-energy sonication (Farhan et al. 2021), and the authors reported optimized conditions for reaching tensile strength and tensile modulus of 123.5 MPa and 16.0 GPa, respectively.

Among the synthetic fibers, glass, carbon and aramid clearly stand out in terms of performance and use. The hybridization of natural fibers and E-glass fibers may achieve high mechanical performance and low cost (Cavalcanti et al. 2019). Increase in tensile strength, bending strength, impact strength, compression-after-impact strength, water absorption performance, thermal stability and durability has been reported for natural-glass fiber hybrid composites compared to the respective bicomponent natural fiber composites (Abu Hena Md et al. 2022; El-Baky et al. 2022; Farhan et al. 2019; Ghani et al. 2022).

In laminates, the improvement may also depend on the stacking sequence (Ghani et al. 2022). Previous studies have cited that balanced contents of natural and glass fibers can yield composites with high performance in terms of low- and high-speed impact (Prabhu et al. 2019; Yasir et al. 2021). In other works, Angrizani et al. (2017) studied different stacking sequences for curaua/glass laminates and reported interesting dynamic-mechanical, Barcol hardness and thermal properties, whereas Fiore et al. (2018) evaluated the bearing behavior of flax/glass laminates using three stacking sequences. Some other studies addressed fatigue properties of kenaf/glass hybrids (Sivakumar et al. 2018) and hydrothermal aging performance of flax/glass hybrids (Calabrese et al. 2019), among other features.

Nevertheless, the literature still lacks studies on the mechanical properties of natural/glass laminates, especially unidirectional ones. In case of hybrid laminates where natural fibers are the outermost layers, they bring interesting esthetic attributes, which may be important in applications such as musical instruments.

As for the hybridization of natural fibers with carbon fibers, although it may be relatively expensive, it significantly increases electrical conductivity, thermal conductivity, mechanical strength and thermal stability, as well as decreases moisture absorption (Farhan et al. 2019; Jagadeesh et al. 2022; Mochane et al. 2019; Ravikumar, Suresh, and Rajeshkumar 2022). According to Lee et al. (2016), predictable and adjustable gains in natural frequency mode and sound radiation rate can also be obtained. This type of hybridization, although already available in some commercial composite products, clearly lacks more studies in the current literature.

Considering that the use of bio-based composites with natural fibers is restricted by unsuitable hygroscopic and mechanical properties, this study investigates the effect of hybridization on interply hybrid jute/glass and jute/carbon laminates manufactured by vacuum infusion, using different stackings of unidirectional reinforcements, to promote physical and mechanical properties.

Material and methods

Materials

Jute fabrics were purchased from Castanhal textile company (Pará/Brazil), which currently supplies jute products including yarns, ropes, fabrics, and bags. The fiber bundles have width of ≈3 mm and the fabrics are mostly unidirectional, with an areal density of 239 g/m^2. Before usage, these fabrics were dried for 2 h at 50 °C in an oven.

Unidirectional E-glass fabric (VEW 090/50) (450 g/m^2) acquired from Owens Corning (Rio Claro/Brazil) and unidirectional carbon fabric (UC300 T700) (368 g/m^2) acquired from E-Composites (Rio de Janeiro/Brazil) fabrics were also used to produce the laminates. Unsaturated isophthalic polyester resin (grade Arapol 70,451) and Butanox 50 as initiator were also used. Since this resin did not present an adequate gel time for the longer infiltrations of the two-component pure glass (G_5) or pure carbon (C_5) fiber composites, 3% styrene (acquired from Fiberglass) was added to the resin.

Vacuum infusion molding

Processing by vacuum infusion was chosen due to its potential to achieve high fiber volume fraction and low void content, as reported in previous studies (Sathishkumar, Naveen, and Satheeshkumar 2014). The molding area was set on a rigid mold and a layer of release agent was applied. The reinforcement layers (jute, glass, or carbon) were stacked (300 mm × 300 mm) on a one-sided mold, a layer of peel ply was added, and a flow mesh was placed over a limited area (the first 50 mm and the whole width). The inlet and outlet gates (spiral tubes) were positioned in the mold, which was sealed using tacky tape, on its periphery, and a vacuum bag film.

The mold cavity was then evacuated, removing air and compacting the reinforcement. Resin entered the sealed cavity through the inlet due to the imposed vacuum (−100 kPa = −1 bar), infiltrating the stack of layers. After complete wetting of the fabrics, resin flow was interrupted, but the vacuum remained applied for 18 h to help removing entrapped air and to minimize thickness changes due to the relaxation of fibers in the decompression. The laminates were allowed to cure at room temperature for 24 h and post-cured at 60 °C for 4 h in an oven. Nine laminates, illustrated in Figure 1, were produced, being three single fibers and six hybrids, namely J_5, J_2GJ_2, JGJGJ, JG_3J, G_5, J_2CJ_2, JCJCJ, JC_3J and C_5, where J, G, and C represent jute, glass, and carbon layers, respectively.

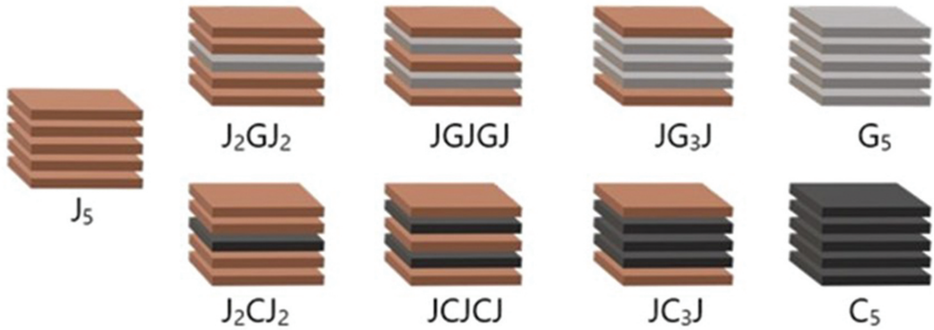

Figure 1. Illustration of the studied two-component and three-component (hybrid) laminates.

Resin characterization

To characterize the resins, the components were mixed (1% initiator in relation to the resin) and cast into silicone molds to produce dumbbell specimens (type IV, ASTM D638). *In situ* curing at room temperature for 24 h and post-curing at 60 °C for 12 h in an oven were carried out, following the resin manufacturer's recommendations. These specimens were tensile tested using an Instron universal mechanical testing machine, model 3382, equipped with a clip extensometer and 5 kN load-cell, at a speed of 2 mm/min, as per ASTM D638. Besides, resin density was determined according to ASTM D792, using distilled water (density 997 kg/m^3).

Laminate characterization

Specimens for characterization were cut from the laminates using a CNC Router machine (model SPL 2015, brand Lexno). The fiber weight fraction (W_f) was defined as the ratio between the fiber mass and the final composite mass. Density was determined through water buoyancy based on the Archimedes principle described in ASTM D792. These samples were hand-sanded using a 400-grit emery paper to remove fuzzy edges from cutting.

Homogeneity of the laminates was evaluated using the C-Scan ultrasound nondestructive technique. The laminate surface was slightly moistened using water and detergent to enhance detection of the ultrasonic signal since the equipment used (Raptor model, NDT Systems) works in pulse/echo mode (bi-polar pulse type). The transducer (0.5 in diameter) was adjusted to a frequency of 2.25 MHz and gain of 24–28 dB. The ultrasonic images were processed using the RapWin software. Readings were taken in relation to the y-axis at a scan index of 2.61 mm. The results obtained consisted of representative images, where the color pattern represents intensity of the detected sound signal.

Tensile tests were performed in accordance with ASTM D3039 on seven samples (dimensions: 250 mm × 15 mm) per group. The tests were carried out at a constant speed of 2 mm/min until rupture. Longitudinal and transversal deformations were measured using a video strain gauge coupled to a universal mechanical testing machine model Instron 3382 equipped with a 5 kN load cell. After tensile testing, the fractured surfaces of the composites were coated with a gold layer and analyzed using a Jeol JSM 6060 high-resolution Scanning Electron Microscope (SEM) at 10 kV.

Three-point bending tests were performed on seven samples (dimensions: 127 mm × 12.7 mm) per group following ASTM D7264. The samples, with span to thickness ratio of 16, were tested at a constant speed of 1 mm/min until a maximum strain of 5%. Short beam strength tests were conducted based on ASTM D2344 using six samples (dimensions: 18 mm × 6 mm) per group, which were tested until rupture at a speed of 1 mm/min. Both tests were carried out using the aforementioned Instron machine.

Water uptake was monitored based on the mass change over time in waterlogged samples. This procedure was conducted based on ASTM D5229 and consisted in a simple immersion in distilled water at room temperature (~20 ºC), which was followed by subsequent weighing up to 540 h of water exposure. The cut surfaces of the samples were not sealed.

All data were separated into groups based on the factors under study and tested for normality and homogeneity of variances, using the Shapiro-Wilk and Levene tests, respectively. To compare the studied groups, one-way ANOVA tests were performed followed by Fisher's LSD mean tests, maintaining a significance level of 1% in all cases.

Results and discussion

Polyester characteristics

Density, tensile strength, and Poisson's ratio of the cured polyester and polyester/styrene were considered statistically similar, being 1.17 and 1.12 g/cm^3, 0.206 and 0.213 MPa and 52.79 and 47.68 MPa, respectively. Elastic modulus of the resin without styrene, however, was higher, 3184 and 2742 MPa, respectively. The presence of styrene can affect the mechanical and thermal properties of unsaturated polyester resins due to changes in crosslink density, which also depends on styrene content and its miscibility in the polyester resin (Rajaee et al. 2019).

Density of jute/glass and jute/carbon laminates

As expected, the higher the number of glass fabrics, the higher the fiber weight fraction and composite density (Table 1). Thus, the highest values were obtained for the pure glass laminate, G_5, followed by JG_3J and JGJGJ. These characteristics were influenced by the distinct areal density of the fabrics used, which was much higher for the glass fabric (450 g/m^2) than for the jute fabric (239 g/m^2). These results are in agreement with previous ones on natural fiber/glass hybrid laminates (Cavalcanti et al. 2019; Gupta and Deep 2019). Distinct fabric compressibility, affecting final thickness, also influenced the final fiber content (Gupta and Deep 2019).

Similarly, the higher the number of jute layers, the lower the fiber content and the density in the jute/carbon hybrid composites (Table 1). The pure carbon composite, C_5, showed the highest values. These results are mostly attributed to the differences in areal density of the fabrics (239 and 368 g/m^2 for jute and carbon, respectively) and the more favorable fabric compaction.

Regarding the hygroscopic behavior of the laminates, the two-component glass and carbon laminates overcame the jute one in terms of performance. The water uptake profiles shown in Figure 2 also indicate that, in general, the water saturation is near to be reached after 600 h of water exposure. Also, the interface region between different adjacent fabrics seems to have increased the water filling and, because of that, the laminates J_2GJ_2, JGJGJ, J_2CJ_2 and JCJCJ presented the worst performance. In this sense, JG_3J and JC_3J stood out in terms of hygroscopic performance among the hybrids, which can be ascribed to the presence of three carbon layers, that absorb less water, and also to the well-bonded block of middle layers. For comparison, the C5 and G5 laminates were also evaluated after sealing of the cut surfaces of the specimens. As expected, water absorption reduced significantly to 2.5% and 7.5%, respectively, being compatible with the values reported by Abd El-Baky and Attia (2019) and Sathiyamoorthy and Senthilkumar (2020).

Kamangar and Shokrieh (2020) explained that, besides the own hygroscopic features of both matrix and fibers themselves, their interface region also plays an important role in water absorption. These authors reported that the water uptake in laminates involves several mechanisms, including effective diffusivity, maximum total moisture concentration, and thickness of each layer. According to Mamalis, Floreani, and Ó Brádaigh (2021), matrix plasticization, glass transition temperature decrease, early formation of fiber-bridging, matrix embrittlement, and decrease in fracture toughness are the main losses in properties due to hygroscopic aging of polymer composites. For instance, He et

Table 1. Fiber weight fraction and density of the two-component and hybrid jute/glass and jute/carbon laminates.

	Weight fraction (%)	Density (kg/m^3)
J5	39.08	$1.194^{\pm0.003}$
J2GJ2	41.14	$1.237^{\pm0.053}$
JGJGJ	48.90	$1.232^{\pm0.008}$
JG3J	51.68	$1.455^{\pm0.007}$
G5	70.74	$1.735^{\pm0.038}$
J2CJ2	45.75	$1.178^{\pm0.006}$
JCJCJ	48.61	$1.153^{\pm0.020}$
JC3J	55.89	$1.351^{\pm0.103}$
C5	67.04	$1.507^{\pm0.073}$

al. (2022) reported decreases in compressive, tensile, and in-plane shear strength of 28.5%, 7.2%, and 16.6%, respectively, for an E-glass fabric/vinylester composite after 90 days immersion in distilled water.

Jute/Glass laminates

The ultrasound images represent maps of sound signals captured along the transverse profile of the plates. Figure 3 shows the images for the jute and jute/glass laminates and fiber-rich zones appear as more amplified signals, with light shades of green and blue. The resin-rich regions appear as darker shades of blue, i.e., a decreased impedance of the captured signal. The images suggest acceptable homogeneity in each plate considering the types of fabrics used and, in some cases, the effect of the presence of the flow-mesh in the manufacturing. Indeed, the ultrasound signal in vacuum infused laminates is usually attenuated near the regions where the flow mesh and the resin inlet and outlet hoses are placed, as in Nunes et al. (2019).

The expected superiority of the pure glass composite was confirmed in the flexural (Figure 4) and tensile (Figure 5) test results. These are justified by the characteristics of the composites, whether two-component or hybrid, such as fiber properties and content, and interfacial adhesion, which favored those with more glass fabrics. Indeed, the G_5 composite presented the highest tensile modulus and strength, which decreased as the number of jute fabrics increased, that is, JG_3J, JGJGJ, J_2GJ_2 and J_5. The G_5 composite presented mean tensile modulus and strength values 158–323% and 163–370% higher, respectively, than the other composites. Indeed, the J_5 composite showed the lowest values in all cases shown in Figures 4 and 5, except Poisson's ratio, with the opposite trend. A lower Poisson's ratio for composites with synthetic fabrics compared to those with natural fibers is widely reported in the literature (Xu et al. 2019).

When a laminate is under uniaxial tension, similar levels of strain are developed in all layers and this justified why only slight differences in tensile properties were found when comparing hybrid laminates, which differed from each other only in the stacking sequences (the same number of layers of each fiber) (Serna Moreno and Horta Muñoz 2022). They also stated that the tensile properties of laminates (elastic modulus and strength) whose surface layers are natural fibers can be reduced due to damage from the grips.

The importance of having rigid and strong fibers as outermost layers was experimentally reported by Xu et al. (2019), who studied jute/glass and flax/glass laminates. This is also clearly seen in the flexural results of this work (Figure 4), that is, since the pure jute and all hybrid laminates had jute layers as the outermost layers, their properties were closer. Indeed, bending loading causes a combined field of stresses in a way that the layers from the neutral line upwards are compressed and from the neutral line downwards tensioned. In this work, the jute fibers were kept always as the outer layers due to esthetic reasons, i.e., the wood-like appearance was valued for its intended application in musical instruments.

The pure glass laminate presented much higher (90%) short beam strength than the pure jute, as shown in Figure 6. Among the hybrids, the composite J_2GJ_2 showed the lowest interlaminar properties

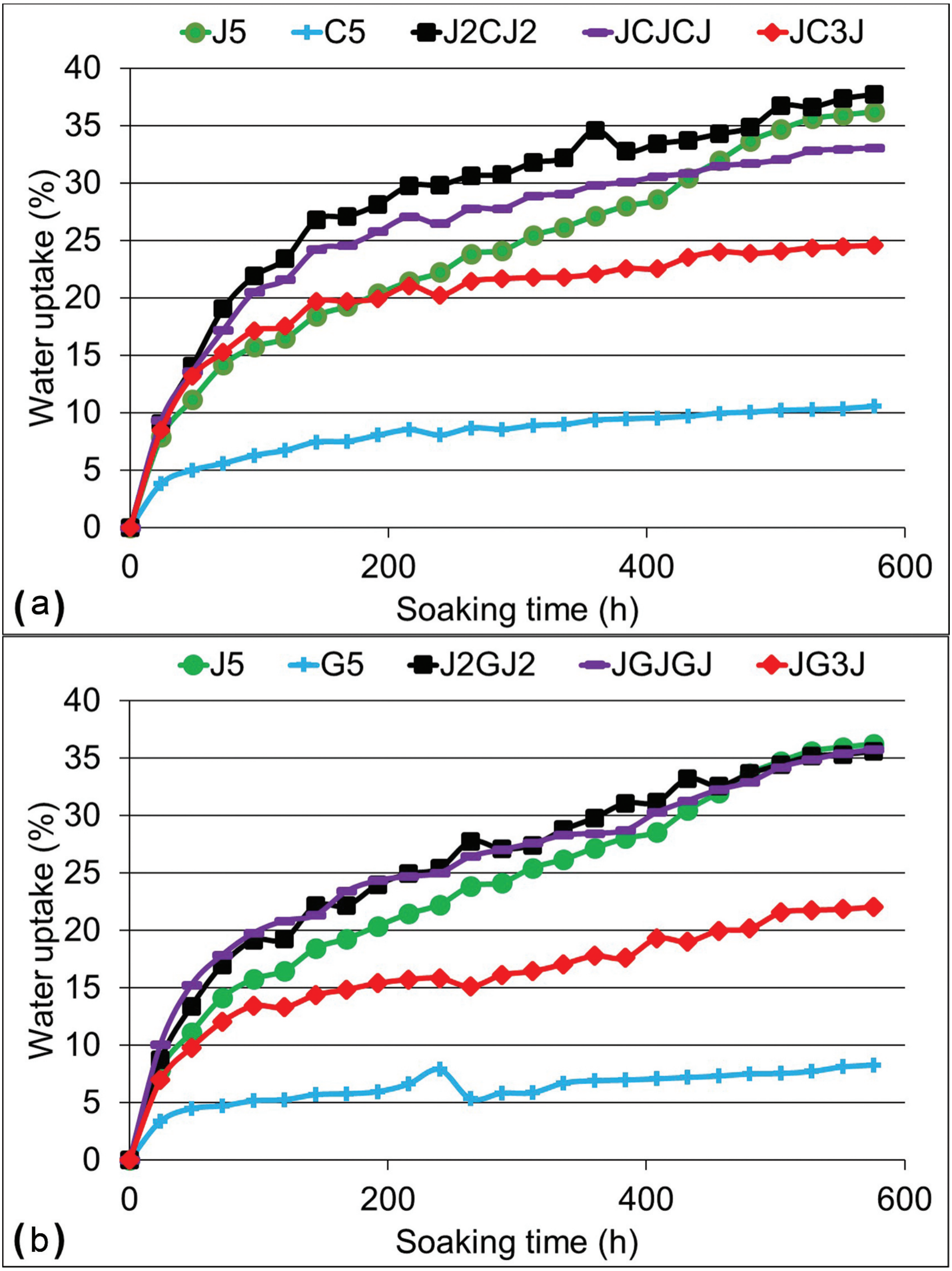

Figure 2. Water uptake of the two-component and hybrid jute/glass and jute/carbon laminates.

(short beam strength), 25–29% lower than the JGJGJ and JG_3J. Therefore, more glass layers was beneficial to this property, but perhaps more important is the fact that jute near the surfaces reduced the measured strength. In their study on hybrid laminates with palm oil fibers and glass fibers, Rayyaan et al. (2020) reported that a poor interfacial adhesion between natural fibers and epoxy led to failures concentrated at this interface, unlike the case of the strong glass-epoxy adhesion, whose most failures were cohesive in the fibers.

Jute/Carbon laminates

For the laminates with carbon fibers, the color map indicated a less homogeneous fiber/matrix distribution (Figure 7). The green shades displayed by the C_5 and JC_3J can be justified by the relatively more difficult overall permeation of the tighter unidirectional carbon fabric, which demanded the addition of 5% styrene to the resin to achieve full infiltration in the available gel time.

The trends in properties for the laminates with carbon layers under both flexure (Figure 8) and tension (Figure 9) were similar to those with glass layers. The pure carbon (C_5) presented the highest

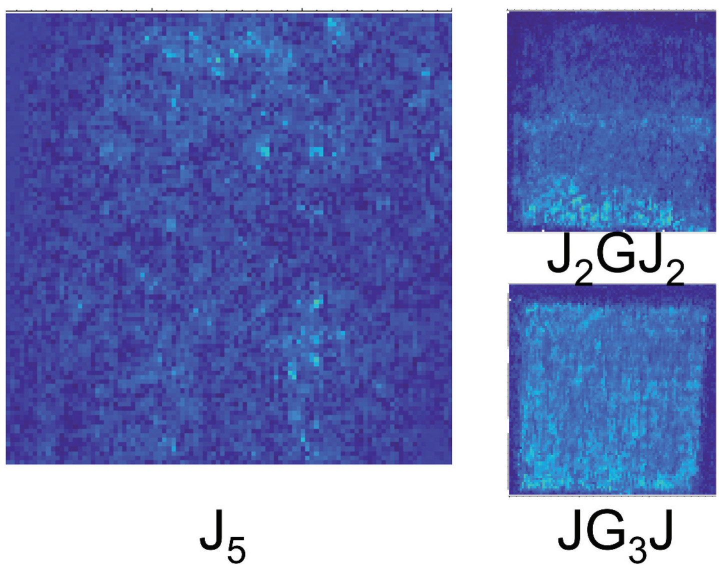

Figure 3. C-scan map of the two-component and jute/glass hybrid laminates.

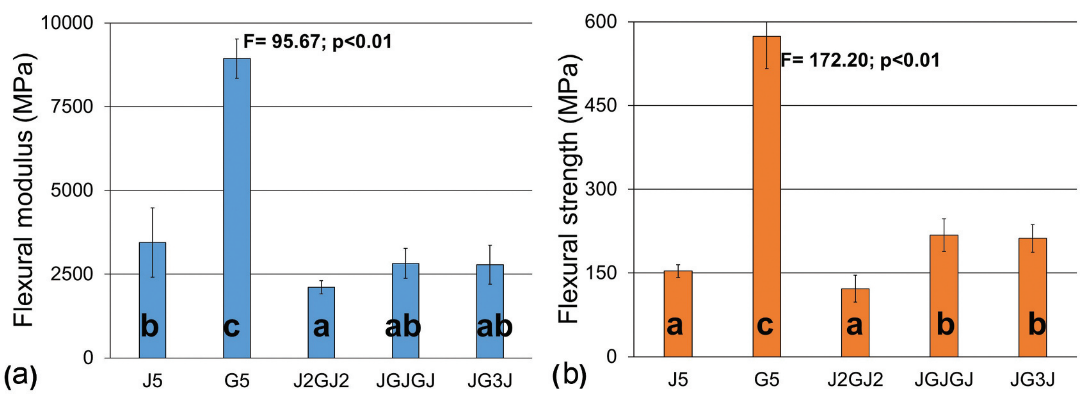

Figure 4. Flexural properties of the two-component and hybrid jute/glass laminates.

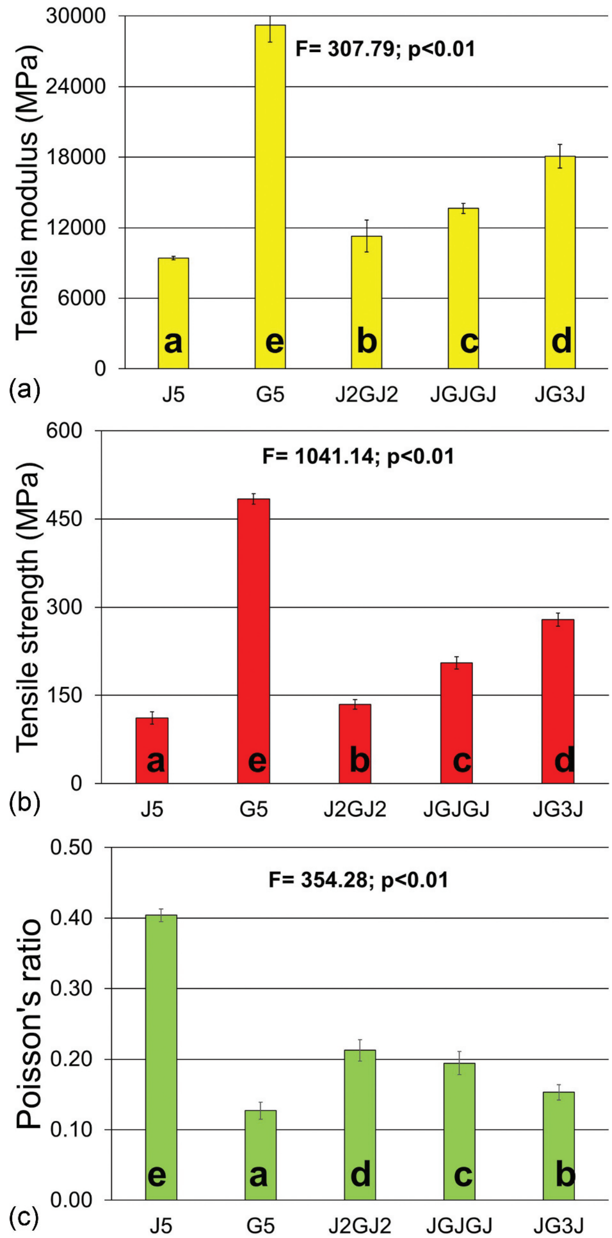

Figure 5. Tensile properties of the two-component and hybrid jute/glass laminates.

stiffness and strength for both loadings. Among the jute/carbon hybrid laminates, the JC_3J clearly presented the highest tensile stiffness and strength, followed by JCJCJ and J_2CJ_2. The percentage differences were of 30–60% and 24–41% for tensile stiffness and strength, respectively. This trend also occurred for the flexural properties (Figure 8), although the differences were less significant because the stronger and stiffer fiber (i.e., carbon) was always as the inner layers of the hybrids. These results can be satisfactorily justified by the number of carbon layers and the type of loadings involved.

Sujon et al. (2020) studied jute/carbon/epoxy laminates with different stacking sequences and fiber orientations manufactured by a similar process, vacuum assisted resin infusion (VARI). The laminate with 10 unidirectional layers (six jute layers and four inner carbon layers, i.e., $J_3C_4J_3$), presented tensile

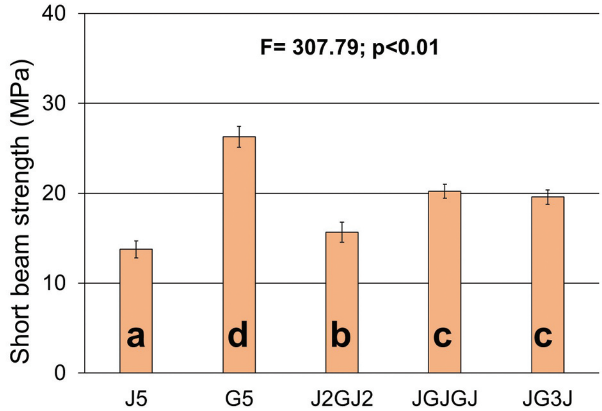

Figure 6. Short beam strength of the two-component and hybrid jute/glass laminates.

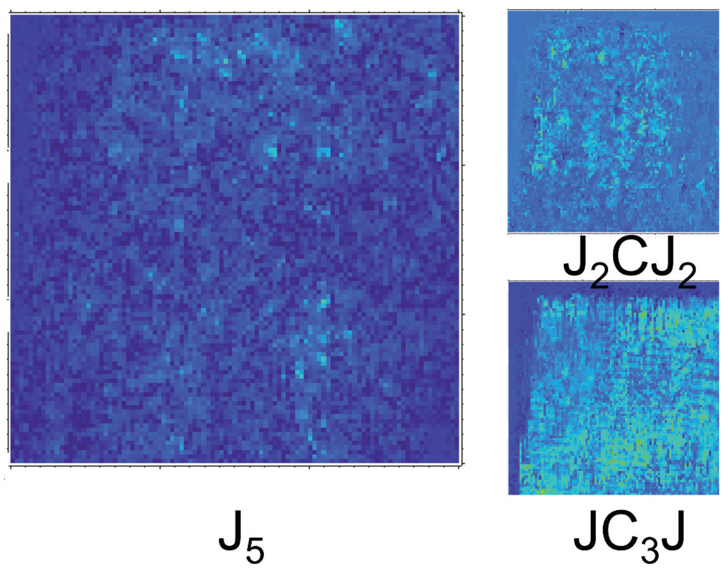

Figure 7. C-scan map of the hybrid jute/carbon laminates.

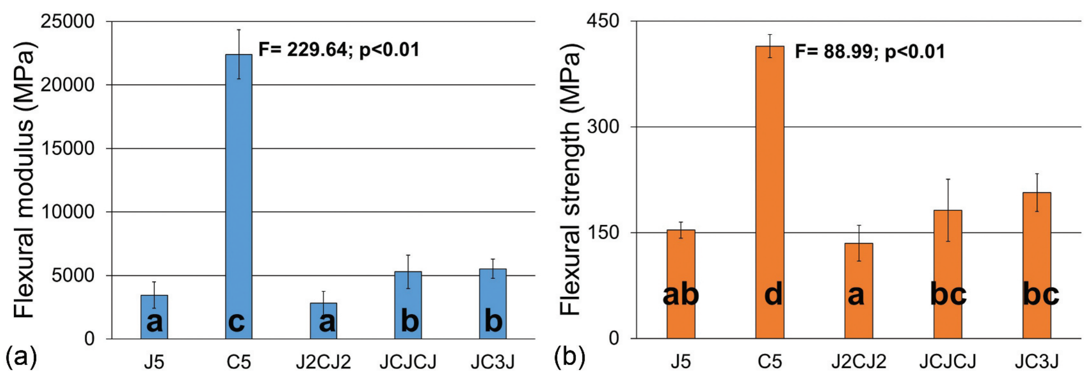

Figure 8. Flexural properties of the two-component and hybrid jute/carbon laminates.

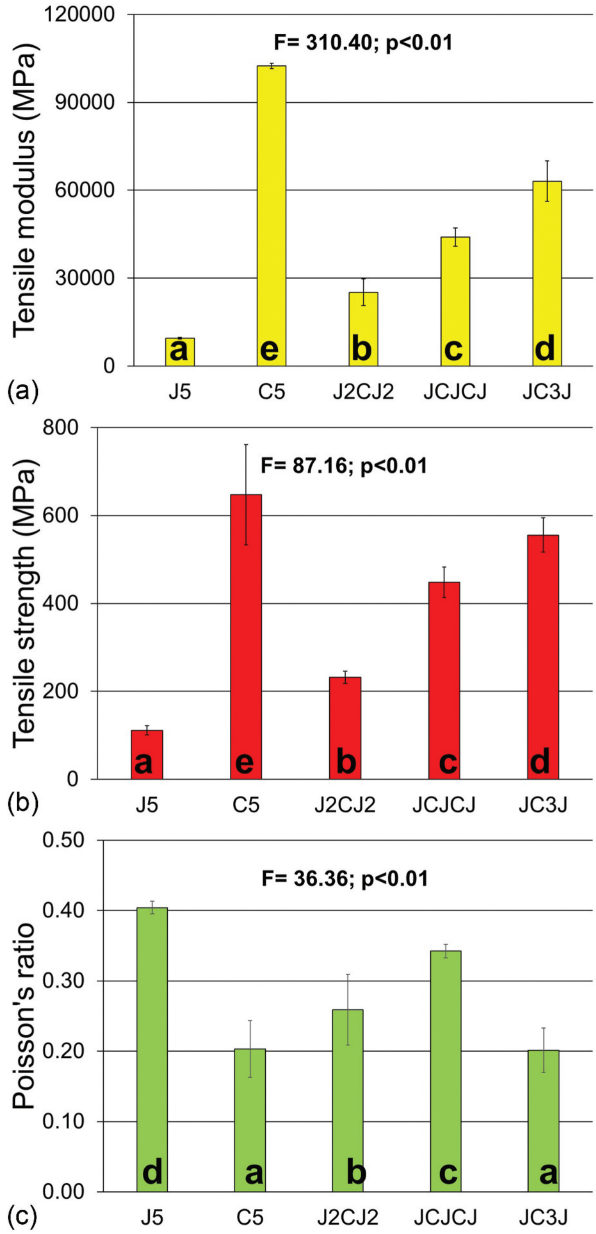

Figure 9. Tensile properties of the two-component and hybrid jute/carbon laminates.

and flexural strengths of 571 MPa and 170 MPa, respectively. The related JC_3J hybrid laminate in the present work, exhibited similar tensile strength (556 MPa) and higher flexural strength (204 MPa) even for a lower performance resin (polyester). This is also in agreement with the fact that the fibers are dominant in these mechanical properties.

Regarding short beam strength, J_5 and the hybrid laminates showed similar values, being inferior to the C_5 composite (Figure 10), with the J_5 composite being 21% smaller than the C_5. In this case, no statistically significant differences were identified among jute and all hybrids. According to Suriani et al. (2021), when interlaminar stresses are applied to laminates whose fibers are all along the plane, both

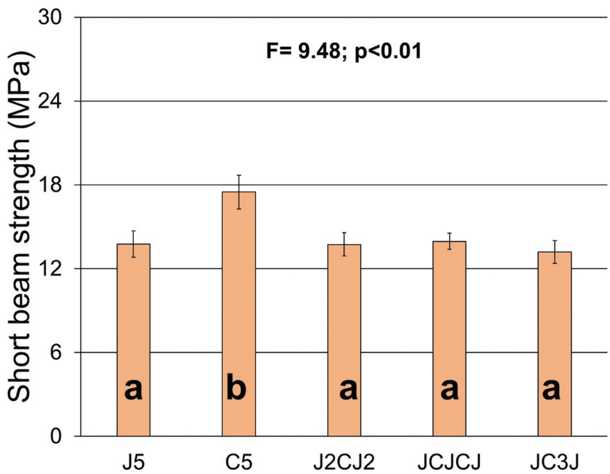

Figure 10. Short beam strength of the two-component and hybrid jute/carbon laminates.

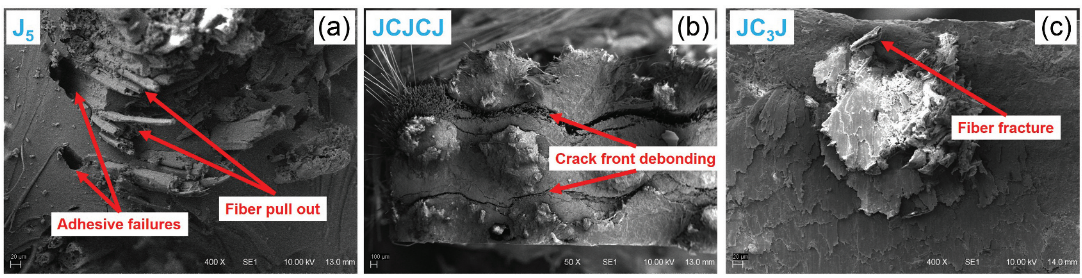

Figure 11. SEM images of fractured surfaces of the laminates: (a) J_5, (c) JCJCJ and (c) JC_3J.

the matrix phase and the fiber/matrix interface are responsible for supporting the loading, and they fail by delamination

Fractography of the tensile-fractured samples was used to reveal different damage mechanisms that occurred in the composites. For the J_5 composite shown in Figure 11a, the failure occurred mainly due to interface failure with fiber pull-out, which occurs when the energy stored within individual stretching bridging fibers reach a critical value below the fiber strength but above the adhesive fiber-matrix strength. In addition, some delamination failures were found in the interlayer regions (Figure 11b). Finally, the composites reinforced with three intermediate laminates showed some fiber-related fractures, as shown in Figure 11c.

Conclusion

In the present work, two-component and three-component composites with unidirectional jute, glass and carbon fabrics were successfully produced by vacuum infusion technique. The studied laminates were all symmetrical, and the jute layers were kept always as the outer layers for esthetics reasons. The ultrasound inspection indicated good general homogeneity in the laminates, although differing among the laminates, which reflected in small deviations in the evaluated mechanical properties.

The hybrid laminates, with more layers of synthetic fibers showed better hygroscopic performance. Regarding the mechanical properties, the hybrid composites displayed generally intermediate properties compared to the two-component laminates. Among the studied hybrids, the number of layers of the synthetic fibers was the main influencing factor, in a way that the JG_3J and JC_3J showed the best general performance, followed by JGJGJ and JCJCJ and, finally, J_2GJ_2 and J_2CJ_2. More specifically, the J_2GJ_2 and J_2CJ_2 composites were overcome by other hybrids in terms of flexural strength and modulus, tensile strength and modulus, and short beam strength. Poisson's ratio was the highest for the jute laminate.

In all, the relative number of natural and synthetic layers can be varied to obtain the required levels of stiffness and strength for a particular application.

Highlights

- Unidirectional jute/glass and jute/carbon hybrid laminates were successfully molded by vacuum infusion
- Different stacking sequences were investigated;
- Ultrasound inspection indicated suitable homogeneity in the laminates, and small deviations were obtained in mechanical and hygroscopic properties;
- In general, the amount of synthetic fibers played a more important role than the stacking sequence;
- JG3J and JC3J are indicated when high mechanical performance is required.

Ethical approval

This manuscript was produced following adequate ethical publication practices, including transparency and integrity.

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Disclosure statement

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