

Mechanical Behavior of Unidirectional Curaua Fiber and Glass Fiber Composites

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Summary: This work intends to promote the use of natural fibers by comparing the behavior of isophthalic polyester matrix composites reinforced with unidirectional curaua fibers with that of unidirectional glass fiber composites. The composites were produced varying the reinforcement angle (0° , 15° , 30° , 45° , 60° , 75° and 90°) with the aim of studying the fiber orientation effect on composite strength. Composites were also made varying the fiber volume fraction (10%, 20%, 30%, 40% and 50%). The efficiency of an alkaline (5% NaOH) surface treatment of the curaua fiber was also evaluated. The unidirectional composites were characterized using tensile, flexural and short beam tests as per ASTM standards. The properties of a lamina reinforced with either glass or curaua fibers were also studied using theoretical micromechanical approach available in commercial software. The curaua fiber alkaline treatment produced higher tensile strength results compared with untreated fibers. The increase in reinforcement angle significantly decreased strength and modulus of the composites, as expected, and the glass fiber composites showed a more pronounced dependence with fiber orientation. Although the glass fiber laminas showed the best mechanical performance, the results obtained with the curaua fibers were considered similar for angles greater than 45° .

Keywords: curaua; glass fiber; micromechanics; natural fibers; short beam

Introduction

Synthetic fibers such as aramid and thermoset resins such as epoxy, polyurethane and unsaturated polyester, which are obtained from petroleum, are thought to have a negative effect on the environment due to their non-biodegradability. Although economical recycling routes for these materials have been increasingly investigated, most of it is currently deposited in landfills at the end of their life cycle.

Increased environmental awareness and new policies focusing on global sustainability have encouraged scientists to develop greener composites.^[1] Composites of low environmental impact are mainly

associated with the use of renewable raw materials, e.g. natural fibers. Indeed, the use of lignocelluloses fibers as reinforcement, replacing synthetic fibers such as fiberglass, is increasing due to favorable properties that include lower cost, biodegradability, lower density, nontoxicity and non-abrasive characteristics. Higher energy demand necessary for the production of fiberglass is another reported factor.^[2]

One of the most promising plant fibers is curaua (*Ananas erectifolius*). The curaua plant is well-known in the Amazon Region in the western area of the Para State (in Brazil), where the first commercial plantations started.^[3] This fiber costs the same as other natural fibers in Brazil, but its strength is believed to be higher than those of coir, sisal or jute, nearly reaching the physical properties of expensive flax fiber or even glass fiber.^[4]

The fibers used as reinforcement in composites may be distributed in a random

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way or aligned in preferential directions (e.g. unidirectional). The composites reinforced with fibers aligned in a single direction are known to be highly anisotropic with high stiffness and strength in the fiber direction and poor mechanical characteristics in the transverse direction. For instance, in a multi-directional composite, with plies in different directions, the first damage (first ply failure) often corresponds to the transverse strength of the plies with unidirectional reinforcement.^[5] Although its importance, unidirectional properties of composites produced with vegetable fibers is rarely seen.

Due to the poor wettability of plant fibers towards polymers, which is a result of their high hydrophilicity, adhesion between these fibers and polymer matrices is generally insufficient. To improve interfacial bonding, surface modification of the fibers may be used.^[6] During alkali treatment, changes in physical structure of the fibers may occur as a result of alkali action which removes waxy materials and impurities.^[7]

Mechanical properties of composites are generally dependent on interfacial strength. One way of addressing that is to evaluate interlaminar shear strength (ILSS), also known as short-beam strength. This technique is increasingly used for characterizing fiber-reinforced composites^[8] and may be employed to evaluate interfacial strength of natural fiber and hybrid composites.^[9–11]

On this context, the aim of this work is to evaluate unidirectional curaua/polyester and glass/polyester composites under tensile, flexural and short-beam tests, and to compare experimental and theoretical properties based on fiber orientation.

Experimental Part

Materials

The following materials were used to produce the composites:

- Polyester resin Arazyn 12.0 from Ara-Ashland;
- Initiator Butanox M-50 (1.5% v/v);

- Glass fiber roving (fiber density = 2.5 g/cm³) from Owens Corning;
- Curaua fiber rope: The curaua ropes were bought directly from a producer from Santarem/Para, in the North Region of Brazil. The fibers had already passed through a preliminary treatment to remove dirt and impurities via washing with water and drying. A second washing/drying was carried out, following by fiber brushing and, finally, twisting of the continuous filaments to produce a rope. The rope was disassembled in the lab to reveal the fiber filaments.

Composite Molding

The composites were molded using either curaua fibers or glass fibers. To address the effect of fiber orientation, they were produced with constant overall fiber volume content (V_f) of 20%. Other composites were produced varying fiber volume fraction (10%, 20%, 30%, 40% and 50%).

Distinct procedures were attempted to obtain aligned curaua fibers, including dry brushing, wet brushing with deionised water and wet brushing combined with pressure for a few seconds at 60 °C in a press. The first was chosen for this study because of its wettability and best molding results. The efficiency of an alkaline surface treatment of the curaua fiber based on immersion in 5% NaOH aqueous solution for 1 h at 25 °C was also evaluated based on the properties of a composite produced with these fibers.

Chemelease 75 from Chem-Trend was applied to the mold surface (inner cavity: 270 × 170 × 3 mm) to act as a release agent. Polyester resin was manually mixed with 1.5 wt% of initiator and then degassed with sonication for 5 min. All composites (isophthalic polyester resin and aligned unidirectional fibers) were compression molded for 70 min at 95 °C with a pressure of 6 ton. Post-curing was performed at 60 °C for 2 h.

Characterization

The specimens were cut from the composite plate following different angles in order to

yield the desired final fiber orientation (0° , 15° , 30° , 45° , 60° , 75° or 90°) and according to the shape required for each ASTM standard and polished.

Tensile tests were performed according to ASTM D3039, in a universal testing machine Instron-8801 Mechanical (Hydraulic Servo), cross-head speed of 2 mm/min, with an extensometer and using a 1000 kN load cell. Six specimens (dimensions: $170 \times 25 \times 3$ mm) were used for each composite family. Flexural tests were performed according to ASTM D790 with the same machine and using a 200 kN load cell. Six specimens (dimensions: $170 \times 12.7 \times 3$ mm) were used for each kind of sample. Short-beam tests were performed according to ASTM D2344 again in the same Instron machine. Fifteen specimens (length = $6 \times$ thickness; width = $2 \times$ thickness) were used for each composite.

Micrographic analysis was also carried out in the non-fractured composites for the study of fiber distribution and void volume fraction, an important factor to influence short-beam strength. For the optical analyses, a trinocular microscope Axio Scope A1 from Carl Zeiss was used, and the composite specimens were built-in acrylic resin followed by grinding/polishing.

Numerical Simulation

The software *The Laminator* (version 3.6) was used to obtain theoretical mechanical properties for comparison. The properties of the constituents (fiber and matrix), their volumetric content and fiber orientation

were used as input in the analysis. This work focused solely on micro-mechanical analysis of the composites, using either glass or curaua fibers, based on experimental or reference properties of the constituents.

Results and Discussion

Tensile Tests

Figure 1a shows the average values of tensile strength for the curaua composites. For the 0° fiber orientation, tensile strength was 160 MPa, and with NaOH treatment this value increased to 180 MPa, the highest value found for this fiber. There was a decrease of nearly 60% in strength, reaching about 50 MPa for the 15° orientation. From 15° to 30° , the decrease was nearly 42%, later stabilizing at about 15 MPa for angles higher than 45° . Regarding modulus of the curaua composites (Figure 1b), the 0° orientation obtained 15 GPa, decreasing to 10 GPa for 15° (a 30% decrease). From 15° to 30° , the decrease was nearly 20% (8.2 GPa), later stabilizing at c.a. 3.5 GPa for angles higher than 60° .

Figure 2a shows mean values of tensile strength for the glass composites. For the 0° fiber orientation, tensile strength was 288 MPa, the highest value for this fiber, decreasing 82% to nearly 53 MPa for the 15° . The 30° showed 26 MPa, later stabilizing in about 5 MPa for angles higher than 30° . Regarding tensile modulus (Figure 2b),

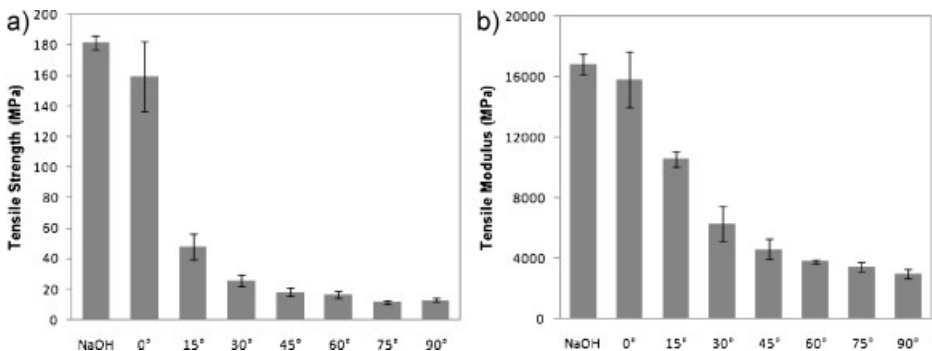
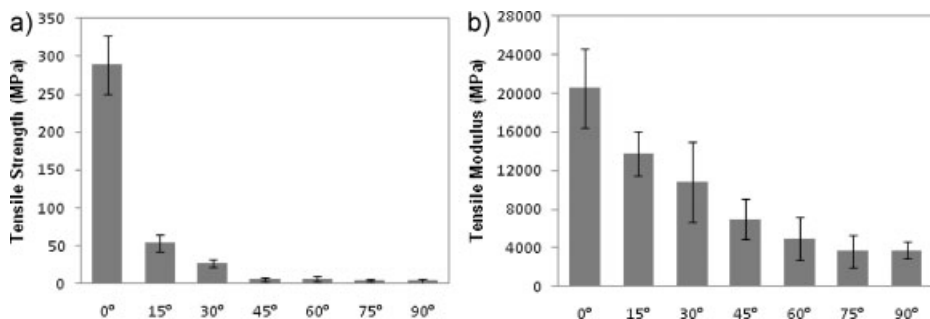


Figure 1.

Mean values of tensile strength (a) and modulus (b) for the curaua composites.

**Figure 2.**

Mean values of tensile strength (a) and modulus (b) for the glass composites.

the 0° fiber orientation reached 20 GPa, whereas for 15° and 30° it dropped to 13.7 and 10.8 GPa, respectively, decreasing further to 5.6 GPa for the 45°, later stabilizing for the steeper angles.

Flexural Tests

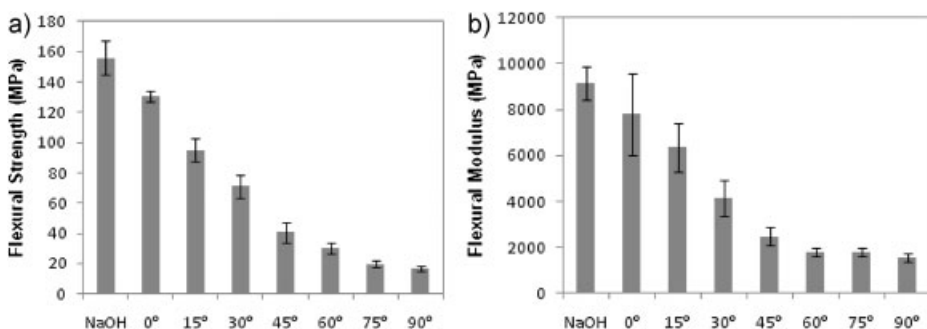
Figure 3a shows the mean flexural strength values for the curaua composites, which decreases for higher orientation angles, as expected. The 0° fiber orientation reached 130 MPa, going to 95, 71, 40 and 29 MPa for the 15°, 30°, 45° and 60°, respectively, whereas the 75° and 90° orientations were in the same range (16–19 MPa). The flexural modulus of these composites (Figure 3b) showed the same pattern, although the decrease with the angle was much less abrupt. For 0°, the flexural modulus was 7.8 GPa, later stabilizing at around 1.7 GPa for angles higher than 60°.

Figure 4a–b, with the mean values of flexural strength and modulus for the glass

reinforced composites, showed the same behavior found for the curaua composites. The 0° fiber orientation reached 439 MPa of strength, decreasing to 8–9 MPa for the 75–90° orientation angles. For flexural modulus, the glass composites obtained 17.2 GPa for the 0° fiber orientation, dropping to 1.2 GPa for the 60° and higher angles.

Short-Beam Tests

Figure 5 and 6 show representative curves of force versus displacement obtained in the short-beam test (ILSS) for the curaua and glass-fiber reinforced composites varying fiber orientation and volume fraction, respectively. Failure of the samples occurred due to interlaminar shear with some influence (damage) from flexural, folding and displacement of the fibers (pull out), and these effects appear to have been magnified by the weak interfacial adhesion found for the natural fiber [12]

**Figure 3.**

Mean values of flexural strength (a) and modulus (b) for the curaua composites.

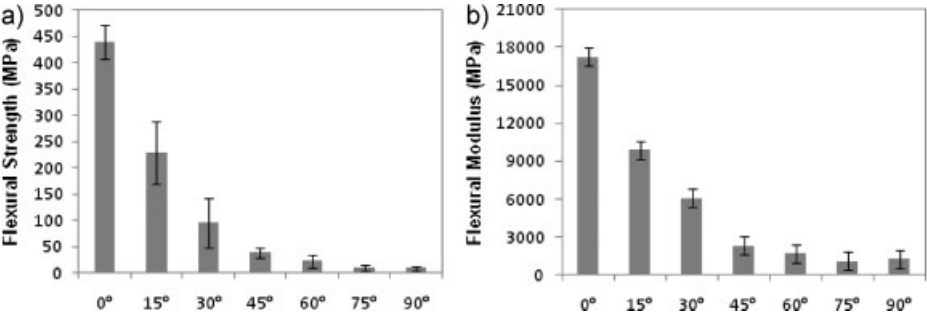


Figure 4. Mean values of flexural strength (a) and modulus (b) for the glass composites.

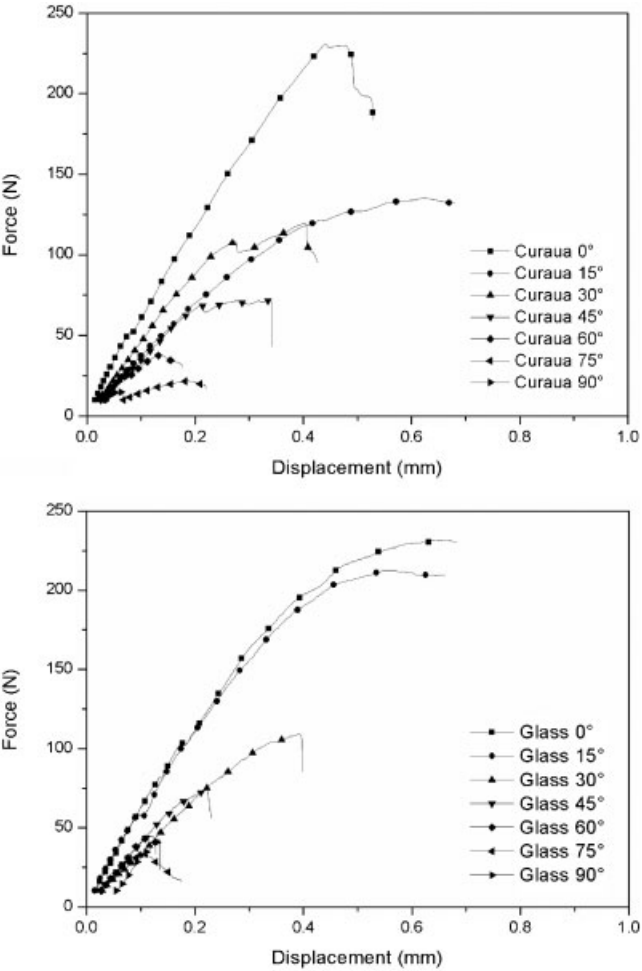


Figure 5. ILSS curves obtained for curaua/polyester and glass/polyester composites for distinct orientation angles.

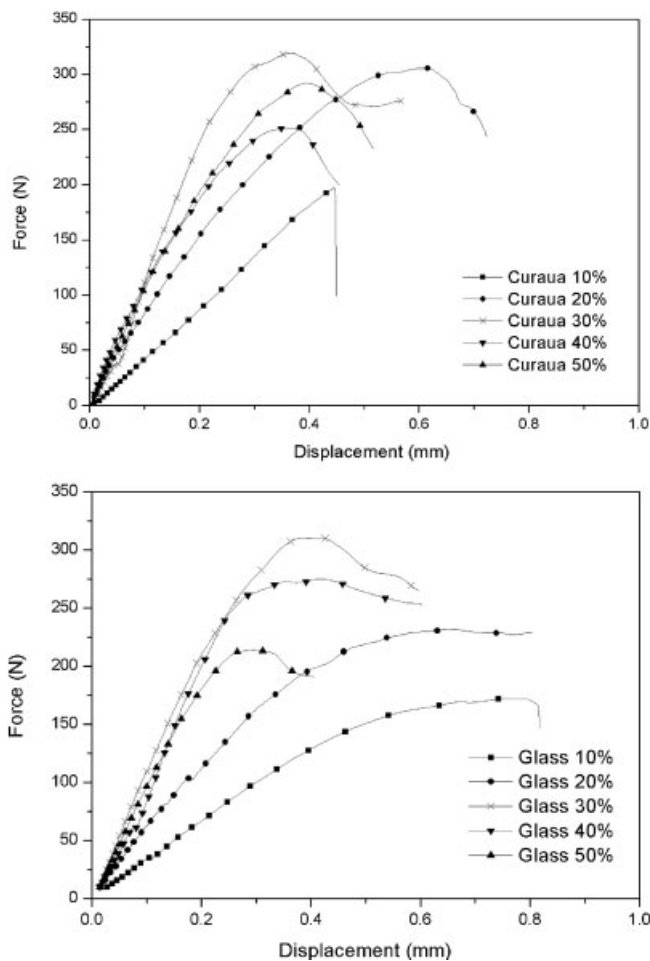


Figure 6.

ILSS curves obtained for curaua/polyester and glass/polyester composites for distinct fiber volume fractions.

which ultimately affected the profile of the curaua curves.

As Figure 7 shows, short beam strength is also influenced by fiber orientation in the

composites, and the 0° orientation again showed the highest strength values for both fibers. Furthermore, the difference between the curaua and glass results were relatively

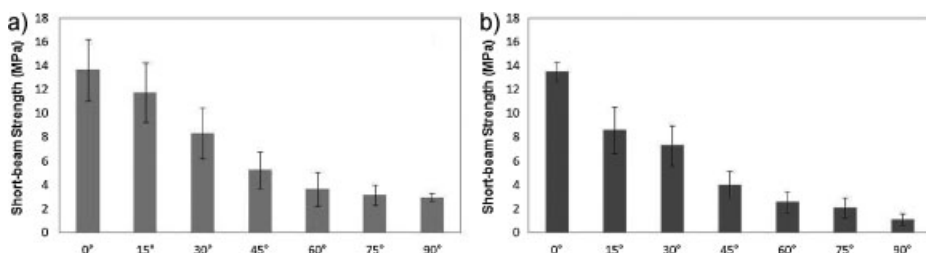


Figure 7.

Mean short-beam strength values for glass (a) and curaua fiber (b) composites.

small. This was attributed to molding difficulties found for the latter, which may have resulted in internal flaws, decreasing the strength values.

As reported in the literature,^[13] short beam strength depends primarily on matrix properties and interfacial fiber/matrix adhesion instead of the fiber properties. Classical Beam Theory states that the distribution of shear stress along the thickness of the sample is a parabolic function that is symmetrical about the neutral axis (maximum shear stress), decreasing to zero on the compression and tensile faces. However, the actual stress field is often dominated by the stress concentration near the area in which the loading nose is in contact with the sample.^[14]

Figure 8 shows the short-beam strength values varying with fiber volume fraction. It is possible to notice that, for glass composites, strength increases from 10% to 30% fiber content, reaching a maximum value of 20.7 MPa, and then decreases for higher fiber loading. In addition, it can be seen that curaua composites show somewhat similar behavior, reaching a maximum (in this case, 17.1 MPa) also for 30% fiber content, and that these values are below those found for glass for all studied volume fractions.

Ahmed et al. (2008) found ILSS of 13.9 MPa for jute/polyester laminates (36% fiber volume fraction), in the same range as that found here for curaua 14.8–17.1 MPa

(for 30–40%). For the glass composites, the maximum value was 20.7 MPa, lower than the values reported by Mathews and Rawlings^[14] – 30–75 MPa for the same type of glass reinforcement but with a different matrix, which is less prone to voids. Wisnom^[15] reported a reduction in ILSS for unidirectional glass/epoxy composites caused by larger discrete voids (diameter: 3 mm) and smaller distributed voids (diameter: 0.28 mm), where the former voids act as cracks initiators under shear stress. To achieve higher ILSS value, Nigel suggested, for instance, the use of a different resin.

Optical Micrographic Analysis

Figure 9–10 show optical micrographs for curaua and glass composites, respectively. In both figures, good distribution of fibers was achieved considering that manual distribution was used. It is also possible to notice the presence of voids (dark areas), which appears to be more accentuated for higher fiber volume fractions, between 40–50% for curaua and 30–40% for glass composites. In some of the images, the glass composites show higher void content in comparison with curaua, which may be explained by the fact that the glass reinforcement was produced by distributing thin glass-fiber bundles (obtained from the roving) parallel to the mold walls. These bundles may pack tightly during compression, preventing adequate wetting of some

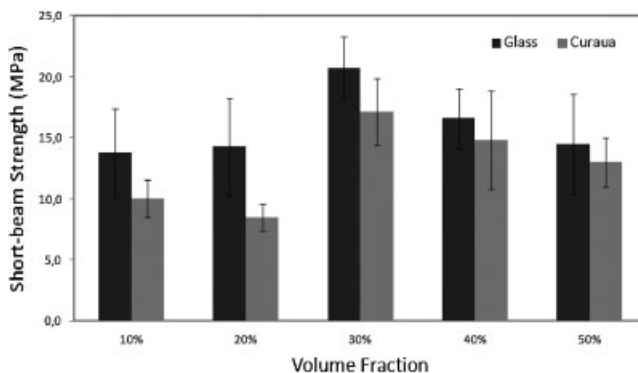


Figure 8.
Variation of short-beam strength with fiber volume fraction.

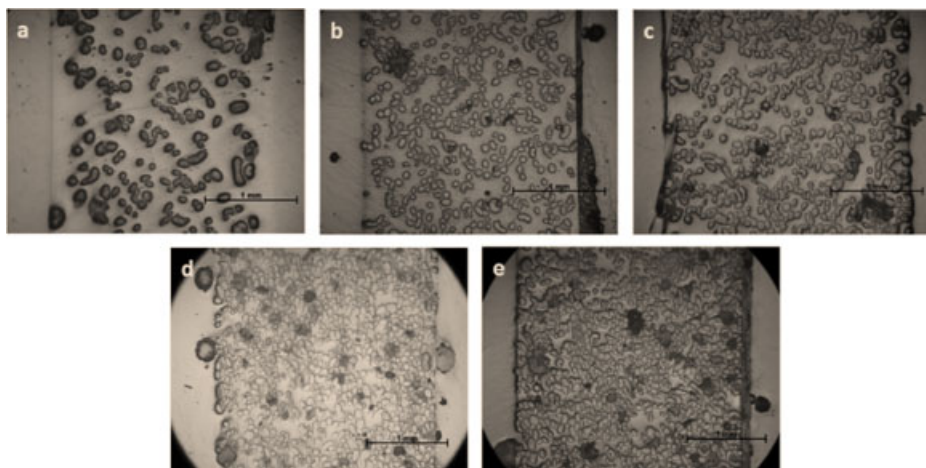


Figure 9.

Micrographics showing the cross-section of curaua-reinforced composites at distinct fiber volume fractions: a) 10%, b) 20%, c) 30%, d) 40%, and e) 50%. (Zoom $10\times$, zoom digital 1.7–2.0).

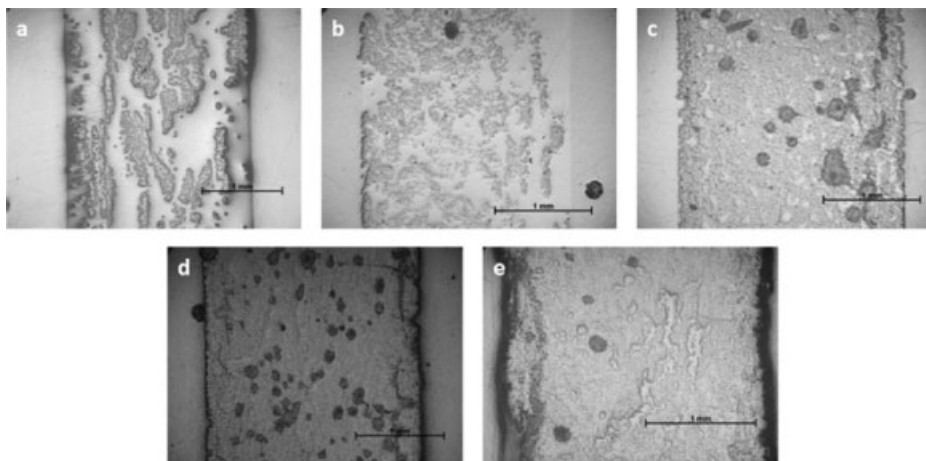


Figure 10.

Micrographics showing the cross-section of glass-reinforced composites at distinct fiber volume fractions: a) 10%, b) 20%, c) 30%, d) 40%, and e) 50%. (Zoom $10\times$, zoom digital 1.7–2.0).

areas of the reinforcement by the viscous resin.

Micro and Macro-mechanical Analysis

The input data used in the theoretical mechanical analysis with the software were:

- i) For curaua fiber: Longitudinal modulus (E_1) = 21 GPa; Transverse modulus (E_2) = 2.8 GPa, Shear modulus (G_{12}) =

4.7 GPa, Poisson's Ratio (ν_{12}) = 0.25, Tensile strength (σ_{1T}) = 580 MPa, Compressive strength (σ_{1C}) = 350 MPa, MPa, Density (ρ) = 1.45 g/cm^3 [2,7,18,19,20]

- ii) For glass fiber: $E_1 = 72.5 \text{ GPa}$; $E_2 = 72.5 \text{ GPa}$, $G_{12} = 27.6 \text{ GPa}$, $\nu_{12} = 0.22$, $\sigma_{1T}^T = 2400 \text{ MPa}$, $\sigma_{1C}^C = 1550 \text{ MPa}$, $\rho = 2.5 \text{ g/cm}^3$ [21–22]
- iii) For polyester resin: $E = 4.3 \text{ GPa}$, $G = 4.27 \text{ GPa}$, $\nu = 0.353$, $\sigma^T = 45 \text{ MPa}$, $\sigma^C =$

Table 1.

Numerical results of tensile strength and modulus for the glass composite.

Glass	Failure Theory	0°	15°	30°	45°	60°	75°	90°
Tensile Strength (MPa)	Max Stress	480.0	132.6	76.5	66.3	46.1	37.0	34.5
	Max Strain	335.8	132.6	76.5	66.3	48.1	37.4	34.5
	Tsai-Hill	480.0	124.8	66.7	47.8	39.5	35.7	34.5
	Hoffman	480.0	135.7	68.8	48.2	39.5	35.7	34.5
	Tsai-Wu	480.0	140.9	71.0	49.3	40.0	35.8	34.5
Tensile Modulus (GPa)		17.9	17.3	15.1	11.8	9.0	7.4	6.9

Table 2.

Numerical results of tensile strength and modulus for the curaua composite.

Curaua	Failure Theory	0°	15°	30°	45°	60°	75°	90°
Tensile Strength (MPa)	Max Stress	190.0	163.8	94.6	81.9	67.9	54.6	51.0
	Max Strain	190.0	163.8	94.6	81.9	70.9	55.1	51.0
	Tsai-Hill	190.0	127.6	82.7	63.8	55.5	51.9	51.0
	Hoffman	190.0	138.6	89.7	67.1	56.7	52.2	51.0
	Tsai-Wu	190.0	143.8	94.7	70.1	58.1	52.6	51.0
Tensile Modulus (GPa)		10.4	10.5	9.9	7.8	5.6	4.3	4.0

55 MPa, Shear strength = 41.9 MPa, $\rho = 1.15 \text{ g/cm}^3$ [23]

Table 1 and 2 show the results for curaua and glass fibers, respectively, using the software for a single 3 mm thick layer. The theoretical tensile strength for the 0° curaua composites was similar to the experimental one, but this did not occur for the glass fiber composite. In comparison with the experimental result (288 MPa), the maximum stress failure theory showed the most similar value (335 MPa) for the glass composite. In general, all experimental results of strength and modulus were below the expected range from the software analysis, which may be explained by actual molding difficulties or inadequate (theoretical) input data used for the numerical evaluation.

Conclusion

The use of the deionised water to align the fibers resulted in a rigid and uniform fiber shell with uniform fiber alignment but sometimes inhibiting resin infiltration, yielding a large number of voids. Despite the less perfect alignment, the dry fiber

brushing method was considered the most efficient, showing lower degree of surface flaws and therefore was used for all composites.

The curaua fiber alkaline treatment produced slightly higher (c.a. 10%) tensile strength results compared with untreated fibers. The increase in reinforcement angle significantly decreased strength and modulus of the composites, as expected, and the glass fiber composites showed stronger dependence with fiber orientation. When fiber alignment varied from 0° to 15°, a decrease in tensile modulus of around 33% was found for both fibers, whereas tensile strength dropped between 70% and 81%, for curaua and glass, respectively. The equivalent decrease in flexural modulus and strength for curaua was around 20% and, for glass fibers, in the 43–48% range.

The difference among experimental and theoretical results was mainly attributed to the theoretical input values used, which may not be representative of the actual used fibers, especially heterogeneous in nature (for curaua). The manual fiber orientation and cutting process, which led to some degree of misalignment, and also the presence of voids in the composite is also partly responsible for that. In spite of

that, somewhat similar values were found for the 0° angle.

In all, although the glass fiber laminas showed the best mechanical performance, the results obtained with the curaua fibers were considered similar to those for glass for angles higher than 45°, thus the former fibers could be used to build laminates without a significant decrease in overall properties.

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