Numerical and Experimental Analyses of Hybrid Composites Made from Amazonian Natural Fibers

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Abstract: The application of lignocellulosic fibers as reinforcements in composite materials has found increasing use in recent years, due to the attractive characteristics of natural fibers such as their low cost, high specific modulus, biodegradability, abundance and with many technical qualities. Natural fiber hybrid composites are very frequently used in automotive aerospace and other industries. In this work, numerical and experimental analysis is carried out to compare curauá, jute and sisal fibers in epoxy composites for use in industry. The most appropriate hybridization effect by establishing the amounts of each fiber on the mechanical properties was considered. Finite Element Models were designed and validated through mechanical tests. The number of Finite Element models and specimens performed was determined through the design of experiments using the Taguchi Method and then the results were statistically validated. Higher strength was obtained in composites made with curauá fiber, followed by jute and sisal fibers. Such behavior was achieved by FEM and experimental tests, revealing an increase in tensile strength by increasing the amount of fibers up to 35% in total. Higher strength was achieved when the composite was made with curauá (20 wt.%), jute (10 wt.%) and sisal (5 wt.%) fibers. The results show a good agreement between the FEM and the experimental tests. Furthermore, the results of the present study were compared with those obtained previously mentioned in the open literature.

Keywords: Hybrid composites, finite element method, natural fibres, mechanical testing.

INTRODUCTION

The application of lignocellulosic fibres as reinforcements in composite materials has found increasing use in recent years to replace synthetic fibres such as glass, carbon and aramid fibres due to the characteristics of natural fibres such as their low cost, low density, high specific modulus, economic and environmental advantages, biodegradable, abundant and with many technical qualities [1-4], These advantages place lignocellulosic fiber composites among high-performance composites with economic and environmental advantages [5-7]. Although completely synthetic composites dominate the automobiles, aircraft, sporting goods, and infrastructure sectors [8-10], they have significant disadvantages such as high input costs, high cost of production, non-recyclability, toxicity, and non-biodegradable [11-13]. Many researchers and various industries have invested in biocomposites for many applications using local natural fibres such as Agave (Agave americana), Sisal (Agave sisalana Perrine ex Engelm), coconut (Cocos nucifera), jute (Corchorus capsularis), flax (Linum usitatissimum), curauá (Ananas Erectifolius), etc. as substitutes for synthetic fibers [14-16]. In the study of Alajmi (2021) [17], sisal fibres were selected owing to their low production costs, sustainability, recyclability, and biodegradability. hydrothermal ageing and mechanical characteristics of sisal fibre-reinforced epoxy composites were determined and compared with glass fibre-reinforced epoxy synthetic composites with good results.

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It is known that the mechanical performance of a composite material strongly depends on the nature, orientation of the fibres, the nature of the matrix and also on the quality of adhesion between the two components [18-21]. Treatment of plant fibers with sodium hydroxide (NaOH) is an effective solution to dissolve their non-cellulosic substances and reduce their sensitivity to moisture or water, and improve fiber-matrix adhesion in composites [22-24]. The presence of these non-cellulosic substances in fibers limits their use in biocomposite development. [25-27]. In order to improve the adhesion of the fibre and reduce water absorption, the surface of the fibre can be modified by physical or chemical methods [28-33]. Due to this, in this work, fibers treated with 5% by weight sodium hydroxide solutions with an immersion time of 4 hours were used, according to previous research recommendations [20].

This work used an epoxy system as matrix phase, which is a thermosetting system widely used in the industry due to its low cost and adaptability to be transformed into large composite structures. Epoxy resins are considered one of the most commercialized classes of thermosets. Several advantages, such as excellent thermal and mechanical properties, easy processability, and low production costs, make epoxy resin thermosets suitable for a wide range of applications. Following their huge commercial production, for applications in, for example, the automotive and aerospace industries, in 2019 the global epoxy market reached 26 billion dollars with an expected increase at a compound annual growth rate of 6.2% from 2020 to 2028 [34-37]. A computational and experimental analysis is carried out to compare curauá fibers, jute and sisal fibers used in epoxy resin matrix composites for use in industry, determining the most appropriate hybridization effect by establishing the proportions and amounts of each fiber in a hybrid composite with better mechanical properties. The number of Finite Element models and specimens performed was determined through the design of experiments using the Taguchi Method and the results were statistically validated, which results corresponded with other works done and published previously.

METHODOLOGY

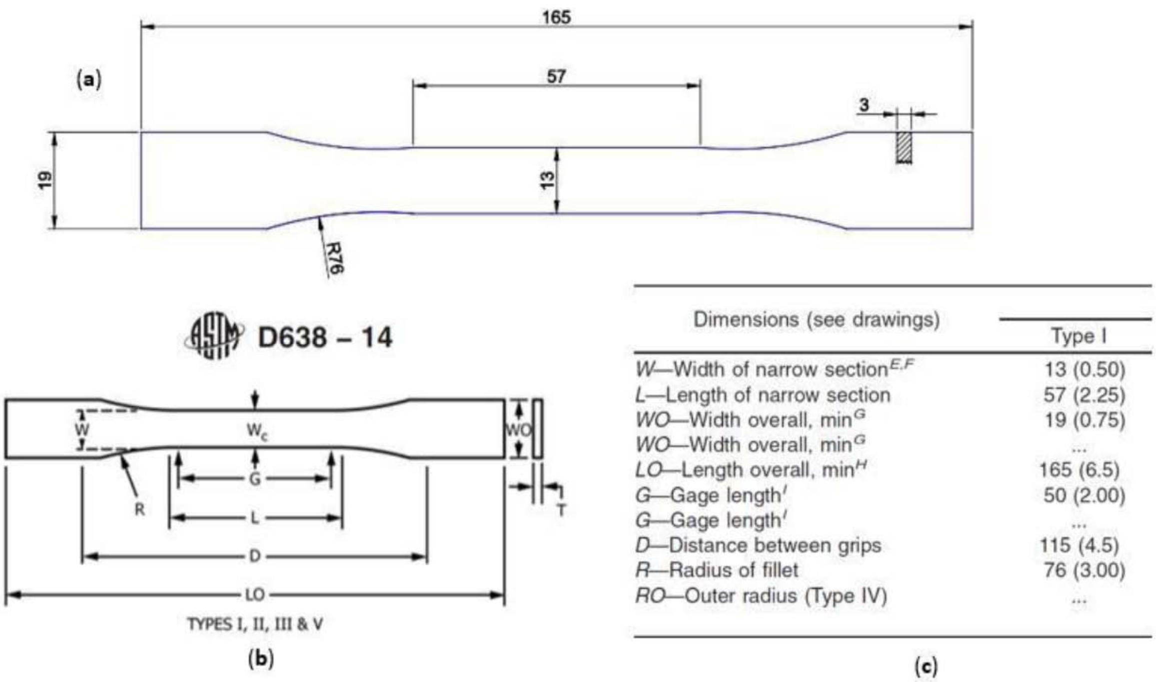
The vegetable fibers used in this work were obtained in Santarem, in the State of Pará (Northern Brazil, Amazon region). The matrix of the composite material was the epoxy resin (bisphenol-epichlorhydrin) with a density of 1.16 g/cm^3 and the epoxy hardener (3154, benzyl alcohol) with a density of 1.005 g/cm^3 supplied by Redelease company in São Paulo, Brazil. First, the design of the experiment was carried out using the Taguchi Method and the MINITAB 18 software using an L25 matrix with 3 factors and 5 levels as can be seen in Table **1**. Taguchi is a robust experimental design used to analyse many parameters with fewer experiments than in traditional experiments. In fact, this technique, widely used to improve the quality of manufactured products, has recently been implemented in the manufacture of green compounds [19, 38]. Taguchi Method was manipulated using Minitab® v.18 software. Table **1** shows the design of Taguchi L25 (orthogonal array), providing 25 experimental conditions. In this orthogonal array, factor levels are weighed in the same way throughout the design [19, 39].

Simulation Part

Following the Taguchi Matrix, a study was carried out using the Finite Element Method (FEM) through Solidworks software code. The FEM has been used in different areas of Engineering, including the evaluation of composite materials with plant fibers [40-42]. The dimensions of the models for both the pure resin and the composite with fibers correspond with the dimensions of the standard for the tensile test D638–14 Type I, as can be seen in Figure **1** [43]. The contact (bonded) between the fibers and the resin of the specimen was ensured to guarantee the transmission of loads, simulating a correct bonding between the fibers and the matrix. To simulate the tensile test on one of the specimen heads, on both flat faces, fixed-type restrictions were placed, and at the other end, a force of 1150 N was applied in the area corresponding

Table 1: L25 Taguchi with 5 Levels 0 5 10 15 20

Type of fibre	Level 1	Level 2	Level 3	Level 4	Level 5
A: Curauá Fibre weight fraction (wt.%)	0	5	10	15	20
B: Sisal Fibre weight fraction (wt.%)	0	5	10	15	20
C: Jute Fibre weight fraction (wt.%)	0	5	10	15	20



Dimensions (see drawings)	Type I
W—Width of narrow section^{E,F}	13 (0.50)
L—Length of narrow section	57 (2.25)
WO—Width overall, min^{G}	19 (0.75)
WO—Width overall, min^{G}	...
LO—Length overall, min^{H}	165 (6.5)
G—Gage length^{I}	50 (2.00)
G—Gage length^{I}	...
D—Distance between grips	115 (4.5)
R—Radius of fillet	76 (3.00)
RO—Outer radius (Type IV)	...

Figure 1: Dimensions of the test body.

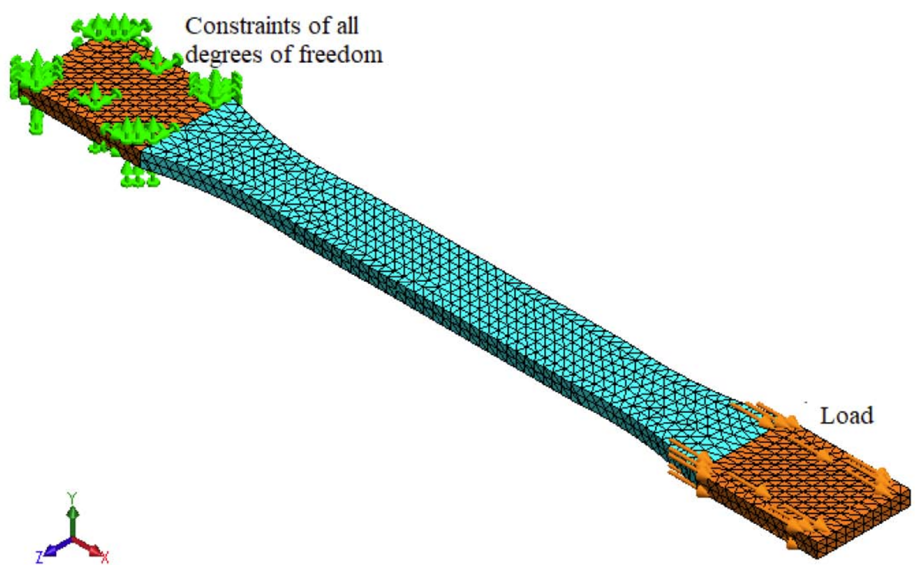


Figure 2: FEM model with the mesh, loads and constraints.

to the faces of the head of the test body as can be seen in Figure **2**.

In this way, 25 models were made, varying the amount of fiber in each case according to Taguchi's experimental design. The results obtained after processing can be seen in Table **2**.

Experimental Part

The experimental part began with the washing and processing of the fibers. This work consisted of beneficed the fibers, which were combed, eliminating existing impurities, washing with tap water and drying at room temperature for 48 hours. Then the chemical treatment was carried out with 5 wt.% sodium hydroxide solutions and 4 hours of immersion time for all fibers using suggestions from results of previous works such as [19]. Before being used in composites, the fibers underwent a drying process. The drying process consists in put the fibres in oven at 60°C for 24 hours and cooled in a desiccator to prevent moisture absorption and the final step being drying at 100°C for

Table 2: Results Obtained from the Computational and Experimental Part

Test Body	A (wt.%)	B (wt.%)	C (wt.%)	von Mises Stress (FEM), (MPa)	Elongation (FEM) (%)	Tensile strength (MPa)	Signal to Noise Ratios
1	0	0	0	39.7	0.82	36±0.94	-
2	0	5	5	143.3	0.78	92±0.67	39.83
3	0	10	10	101.5	0.66	102±0.67	41.54
4	0	15	15	77.99	0.72	125 ±0.66	39.91
5	0	20	20	66.06	0.98	98±0.67	40.76
6	5	0	5	176.3	0.76	97±0.67	38.63
7	5	5	10	118.9	0.67	104±0.67	40.79
8	5	10	15	96.61	0.71	127 ±0.66	41.46
9	5	15	20	84.29	1.24	98±0.67	41.17
10	5	20	0	105.5	0.65	121 ±0.66	39.83
11	10	0	10	121.6	0.64	106±0.67	38.47
12	10	5	15	96.51	0.7	128 ±0.66	40.73
13	10	10	20	72.54	1.18	98±0.67	41.40
14	10	15	0	105.3	0.654	124 ±0.66	41.22
15	10	20	5	89.53	1.27	136±0.84	40.05
16	15	0	15	91.64	0.69	125 ±0.66	38.63
17	15	5	20	80.35	1.07	98±0.67	40.79
18	15	10	0	102.1	0.64	128 ±0.66	41.46
19	15	15	5	85.80	0.73	140±0.84	41.17
20	15	20	10	74.16	1.28	92±0.67	39.83
21	20	0	20	77.80	1.02	98±0.67	38.47
22	20	5	0	95.63	0.61	131 ±0.66	40.73
23	20	10	5	83.87	1.27	143±0.84	41.40
24	20	15	10	71.34	1.27	92±0.67	41.22
25	20	20	15	116.0	1.45	61±0.55	40.05

50 minutes to remove all moisture during manufacturing the composites.

Composite plates were made in a mold as shown in Figures **3** and **4**. Figure **3a** shows the mold filled with the epoxy resin components already mixed without fibers in the curing process. After the material has cured, the composite plate is extracted from the mold with the help of ejector screws as shown in Figure **3b**. Subsequently, the specimens were cut in a laser cutting machine as shown in Figures **5** with the "Dog Bone" format according to the standard for tensile tests [43]. Before performing the tensile tests, the specimens were placed in an oven at 60°C for 2 hours to increase resistance and then 24 hours at room temperature to relax the structure. Five replicates were manufactured for each experimental condition according to the Taguchi matrix, totaling 125 specimens.

The tensile tests were performed on an Instron model 5984 universal testing machine with a load cell of 150 kN and a speed of 5 mm/min, as can be seen in Figure **6**. The results can be seen in Table **2**. Finally, for the analysis of the results, ANOVA for tensile strength was used and the regression equation (Equation 1) was determined. The standardized effect of the factors is examined by preparing a Pareto chart (Figure **9**), which depicts the most influential factor in the response.

RESULTS AND DISCUSSIONS

Table **2** shows the results obtained in all models analyzed by the Finite Element Method and the tensile

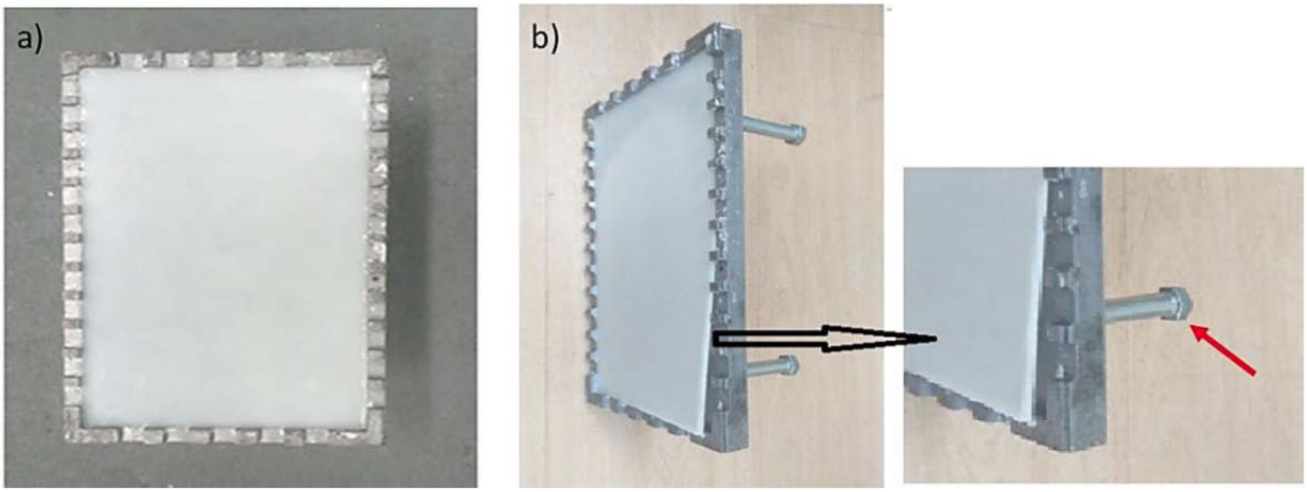


Figure 3: Manufacture of plates: **a**) curing process, **b**) extraction the plate of de mold.

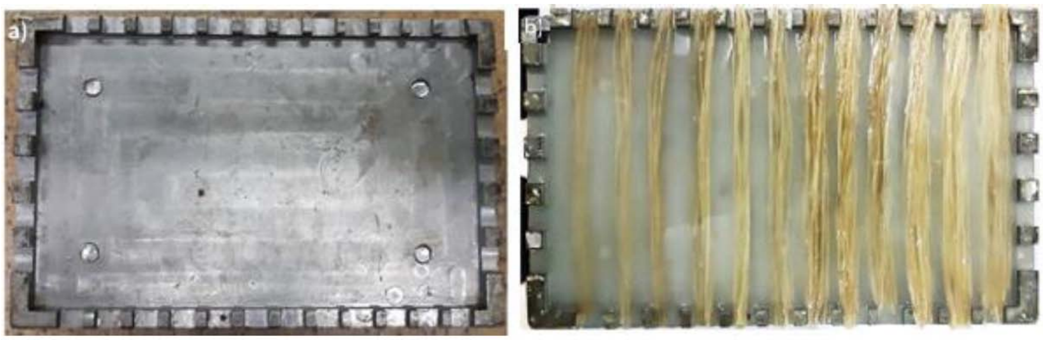


Figure 4: Mold filling: **a**) Empty mold, **b**) Mold with fiber groups being accommodated.

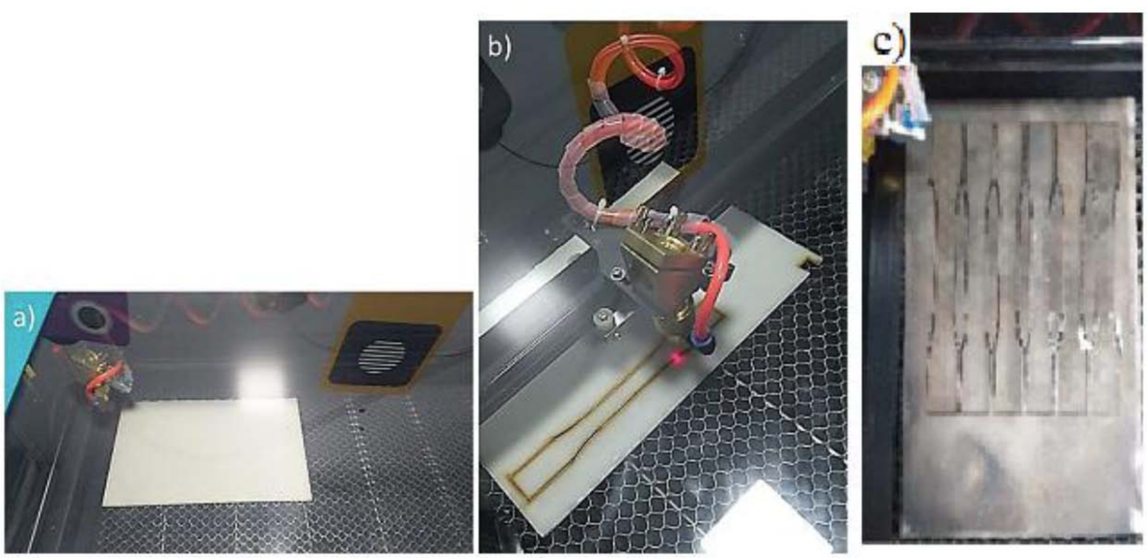


Figure 5: Laser cutting of the specimens: **a**) Positioning of the plate on the machine, **b**) Start of cutting the specimens, **c**) Finalization of the cut of the hybrid plate with jute.

tests for all specimens according to the Taguchi matrix. It can be seen that when increasing the fiber content up to 35 %wt., increases the tensile stress, especially when the curauá fiber content is higher. Table **3** shows the rank based on Delta statistics, which compare the relative magnitude of effects. Taguchi assigns 1 to the highest Delta Value, 2 to the second, and so on. In this case, curauá fiber is the major factor contributing to the

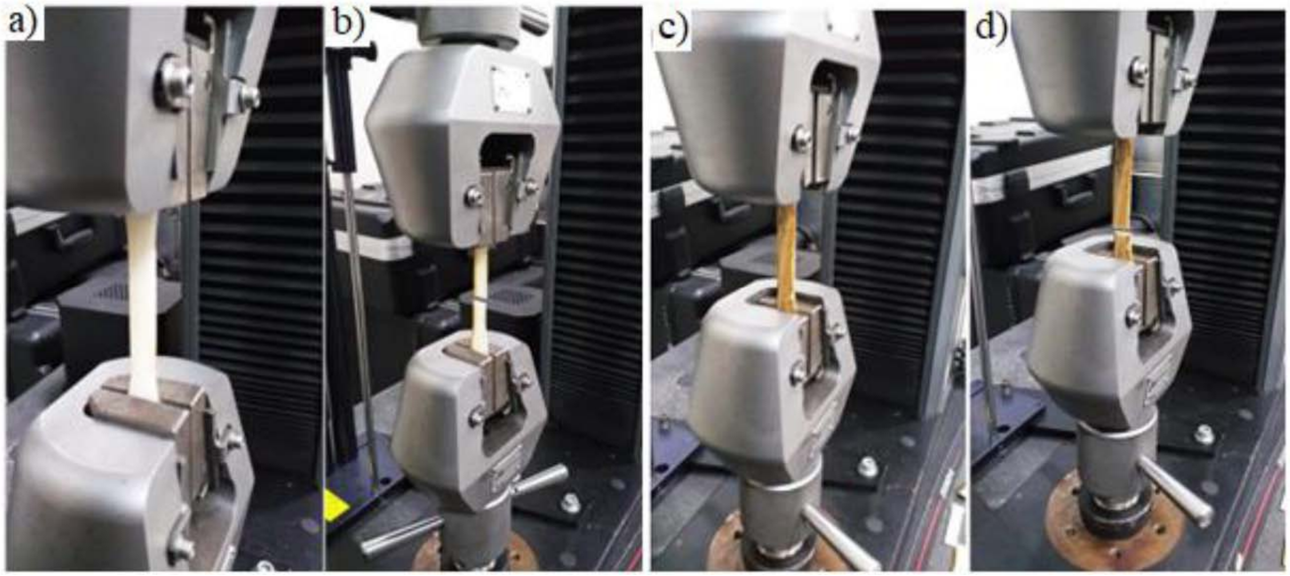


Figure 6: Tensile tests **a**)- Beginning of the tensile test on the pure resin specimen, **b**)- Fracture moment in this specimen, **c**)- Beginning of the tensile test on the resin and curauá fiber specimen, **d**)- Moment of fracture in this specimen.

increased tensile strength of the composites, followed by the sisal and jute fibers.

Figure **7** shows six cross-sections of specimen models (1, 2, 14, 15, 24 and 25) simulated by the FEM based on the Taguchi matrix. These sample conditions were chosen based on their tensile behavior (von Mises). Two images of each are shown: (a) before and (b) after processing. The amount of fiber in each model corresponds to % by weight.

Model 1 is composed only of polymer. Model 2 is composed of polymer and Sisal (5 wt.%) and Jute (5 wt.%) fibers (corresponding to pink and yellow dots, respectively). Model 14 is composed of polymer and fibers of Curauá and Sisal (yellow and blue dots with 10 and 15 wt.%, respectively). Model 15 is composed of polymer and fibers from Curauá, Sisal, and Jute (blue, yellow, and pink dots with 15, 20, and 5 wt.%, respectively) and so on, respectively, for each model.

Model 2b shows that twelve Sisal fibers and twelve Jute fibers reach approximately the same stress values, exhibiting a red color for the stress field. When Curauá fibers are introduced (Models 14b, 15b and 24b, Figure **7**) because they are more resistant, they absorb more load, these fibers being shown in red tones (higher tensions) and the rest of the fibers in green-yellow tones (lower tensions). Model 25b does not show the same behavior, possibly due to the large amount of Cuarauá, Sisal and Juta fibers (20, 20 and 15 wt.%) in the cross-section with a total of 134 fibers (49, 49 and 36, respectively). This finding reveals that both the fibers and the matrix reach similar values of tension, due to the uniform redistribution of the stress field.

The amount of fiber in each model corresponds to % by weight. It can be seen in Figure **2b**, that the Sisal and jute fibers are equally loaded (sample2) and when introducing curauá fibers they absorb much more loads because they are more resistant (sample 15, Model 15b, Figure **7**).

According to the Taguchi matrix, there is some variability in terms of the number of fibers and the order in which the experiments are carried out, that is, there is an approximate behavior of a broken line (zigzag) formed by segments that grow and decrease (stress values) (Figure **8**). This behavior is observed for both tests (FEM and Experimental). Experimental stresses tend to increase slightly with increasing fiber content, while numerical tests decrease slightly at approximately 15 MPa.

The experimental data is transformed into a signal-to-noise ratio (S/N) to determine the optimal parameter configuration to maximize tensile properties. As Taguchi's analysis aims to maximize the tensile strength, the S/N ratio criterion chosen is the larger is better (LBT) [7]. For the analysis of the results, ANOVA for tensile strength was used and the regression equation (Equation 1) was determined. The standardized effect of the factors is examined by preparing a Pareto chart (Figure **9**), which depicts the most influential factor in the response. The analysis

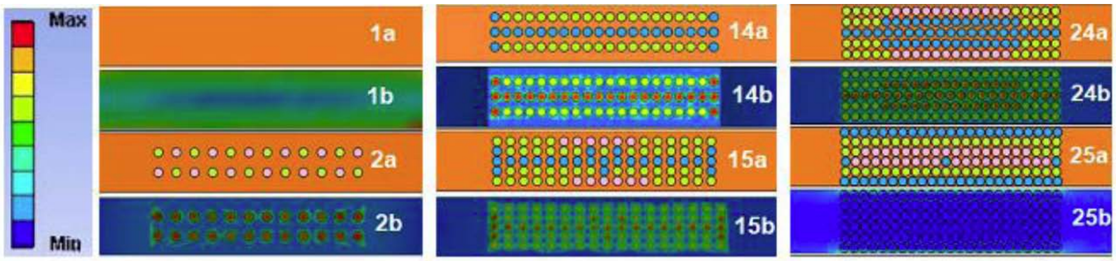


Figure 7: Finite Element Model of 6 tests bodies (1, 2, 14, 15,24, 25), where latter (**a**) not processing and letter (**b**) after FEM processing.

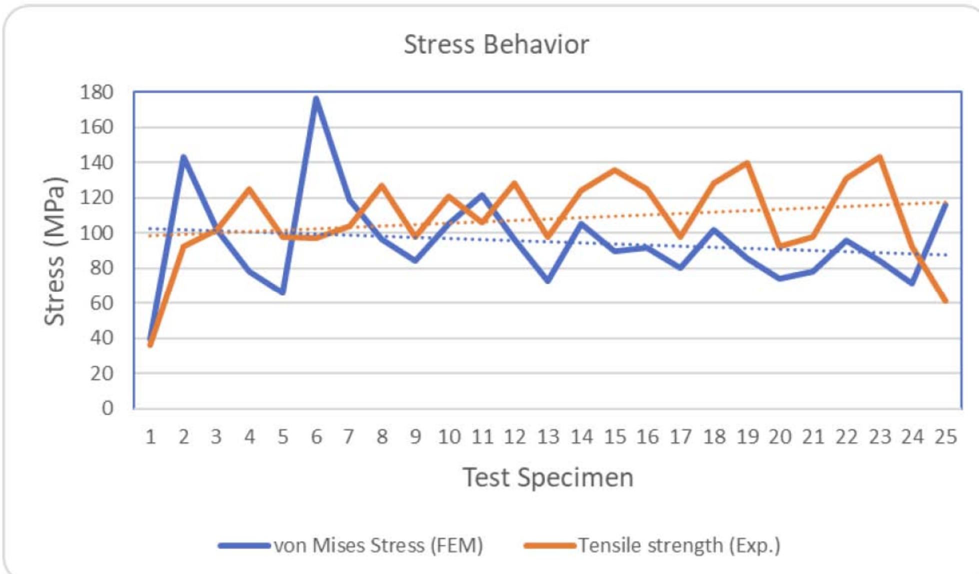


Figure 8: Behaviour observed for both tests (FEM and Experimental).

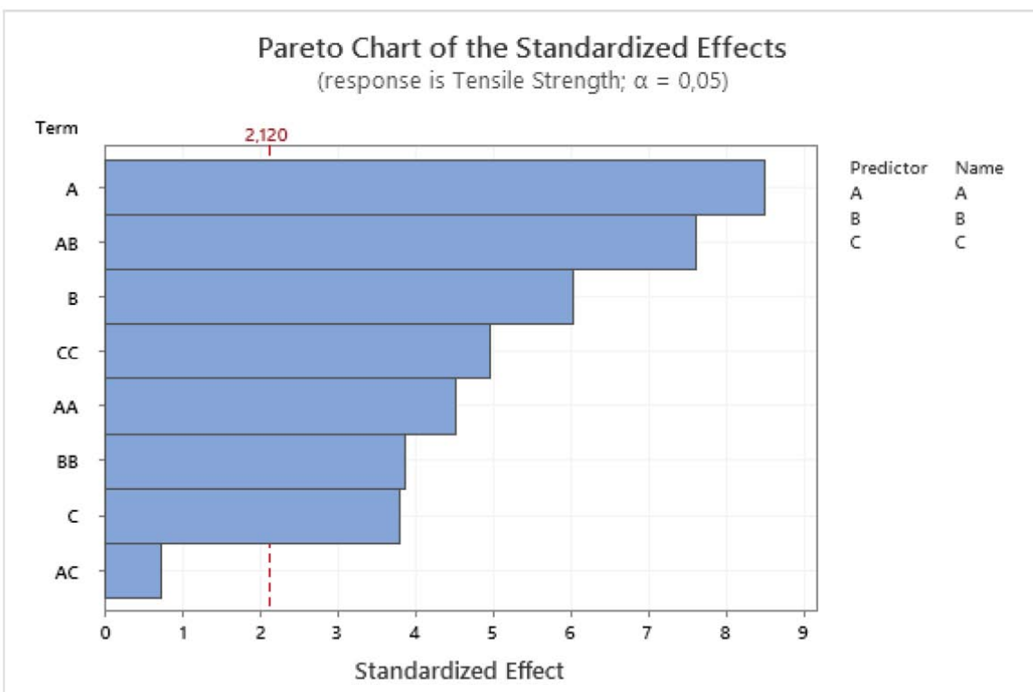


Figure 9: Pareto chart of the standardized effects.

suggests that the curauá fibre amount is the most effective factor, significantly contributing to the tensile strength.

Regression Equation

Tensile Strength = 35.70 + 9.18 A + 8.40 B + 4.01 C - 0.2046 A*A - 0.2023 B*B - 0.2594 C*C - 0.3977 A*B - 0.0389 A*C (1)

Table 3: Taguchi Ranking for Tensile Strength (Larger is Better)

Level	A	B	C
1	90.60	92.40	108.00
2	109.40	110.60	121.60
3	118.40	119.60	99.20
4	116.60	115.80	113.20
5	105.00	101.60	98.00
Delta	27.80	27.20	23.60
Rank	1	2	3

CONCLUSIONS

Through the results of the computational part of the work, it can be seen that when increasing the amount of fiber, the von Misses stresses and deformations decrease, which improves the tensile strength of the specimens, which is verified in the results of the tensile tests. In the experimental part, it was found that when increasing the amount of fibers, the tensile stress increased up to an amount of vegetable fiber equal to 35 wt.%, especially when the curauá content is larger.

DECLARATION OF COMPETING INTEREST

The authors declare no conflict of interest.

CREDIT AUTHOR STATEMENT

Gilberto Garcia del Pino Writing original draft, Abderrezak Bezazi Conceptualisation, Haithem Boumediri Software, César Alberto Chagoyen Méndez Resources, Antônio Claudio Kieling Data curation, José Costa de Macedo Neto Methodology, Aristides Rivera Torres Conceptualisation, Marcos Dantas dos Santos and José L Valin Formal Analysis, Sofia Dehaini Garcia Writing review, Tulio Hallak Panzera and Francisco Valenzuela Supervision.

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