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Study of the effect of variations in fiber orientation on the tensile strength properties of polyester composites reinforced abaca fiber

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Abstract. A composite is a material formed from a combination of two or more constituent materials using a heterogeneous mixing process, whose mechanical properties vary. The aim of this research is to compare the tensile strength values of abaca banana stem fiber polyester composites with variations in fiber orientation. The fiber orientation used is parallel, random and woven. The method used is a hand lay-up press with a fiber volume fraction of 30% and the resin itself uses BQTN 157 EX polyester resin with a hand lay-up method using a glass mold. The test was carried out by tensile testing using the ASTM D3039 measurement standard and macro photos. The results of research on tensile testing show that composites with variations in parallel fiber orientations reinforced with abaca banana stem fibers have an average tensile strength of 39.63 MPa, variations in random fiber orientation have an average tensile strength of 32.87 MPa and variations in fiber orientation woven has an average tensile strength of 25.90 MPa. From the results of macro photo fracture observations, it was found that the type of fracture is a brittle fracture on an uneven fracture surface which causes fiber pull-out where the fibers appear to be coming out of the specimen because the matrix and fibers are not strongly bonded and the fracture is also caused by voids near the fibers.

Keywords: Composite, Abaca Fiber, Fiber Orientation, Tensile Strength, Macro Photo

1. Introduction

The development and application of composite materials has grown and in various sectors, including in this region. Composites are used in household products and industrial applications, spanning small-scale enterprises to large-scale manufacturing industries. Their increasing popularity is attributed to their superior properties compared to conventional engineering materials. Composites are recognized for their high strength, excellent corrosion resistance, cost-efficiency, and other advantageous characteristics. Polymer-based composites comprise a polymer resin matrix (either thermoset or thermoplastic) reinforced with fibers, which can be natural or synthetic. The fibers are available in different forms, like continuous long fibers, short fibers, and woven configurations. Each form has unique mechanical properties that depend on how the fibers are arranged within the composite [1].

Composites are defined as engineered materials formed by combining two or more distinct constituents to achieve superior performance compared to individual components. These materials comprise two primary elements: a reinforcement material, which provides strength and rigidity, and a matrix material, which binds the reinforcement and protects it from environmental and mechanical stresses. Reinforcements, such as fibers, are strong, rigid, and brittle, while matrix materials, often polymers, are ductile, flexible, and chemically resistant [6]. The matrix plays a crucial role in transferring loads to the reinforcements, ensuring their efficient mechanical performance under stress.

Abaca fiber *(Musa textilis),* derived from the banana plant, is a natural fiber with considerable potential as reinforce composite materials. This fiber is renowned for its high tensile strength, exceptional resistance to seawater, and natural durability against microbial degradation. Incorporating abaca fiber into polyester composites has shown the potential to enhance their mechanical properties, encompassing tensile strength, stiffness, and wear resistance. However, to improve the interfacial bonding between abaca fibers and the polyester matrix, alkali treatment with sodium hydroxide (NaOH) is employed. This process removes impurities, changes the fiber's surface characteristics, and enhances its compatibility with the matrix, resulting in improved overall composite performance [11].

The mechanical properties of fiber-reinforced composites are influenced by the orientation of the fibers. Different fiber orientations produce varying mechanical characteristics. Common fiber orientation patterns include unidirectional (parallel), pseudo-isotropic (random), and bidirectional (woven). In fiber-reinforced composites, fibers function as the primary load-bearing component, with the composite's strength dependent on the inherent strength and arrangement of the reinforcing fibers. Smaller, well-arranged fiber components yield higher material strength because of reduced material discontinuities. Fiber orientation, which encompasses variations in angle and layout, is a critical factor in determining the tensile strength and overall mechanical performance of composite materials [7].

Zulfan et al. (2021) conducted a study to examine the tensile strength of polyester composites reinforced with abaca fibers under different fiber orientations, including random, longitudinal (parallel), and woven configurations. Tensile tests were performed on composites fabricated using the hand lay-up method. Composites with woven fiber orientation had a tensile strength of 13.46 kgf/mm^2, those with random orientation had a strength of 1.64 kgf/mm^2, and those with longitudinal orientation achieved 14.64 kgf/mm^2.

This study aims to further explore and compare the tensile strength of abaca fiber-reinforced polyester composites under three distinct fiber orientations—parallel, random, and woven. Additionally, it investigates the fracture patterns observed during tensile testing through macro-photographic analysis, providing valuable insights into the mechanical behavior and failure mechanisms of such composites.

2. Method

2.1 Fiber Processing

Abaca fibers were got from the village of Paloh Mampree, in Peusangan Siblah Krueng District, Bireuen Regency, Aceh Province, Indonesia. The abaca variety used was the red variety, with banana stalks aged between 9 and 24 months. The processing steps were: Abaca banana stalks were harvested (cut) from plantations or forests into pieces 50 cm, and their outer layers (sheaths) were separated. The sheaths were soaked in water using the water retting method for 14 days. Once the fibers were formed, they were washed with water and combed to remove impurities. The combed fibers were then dried under sunlight.

2.2 Composite Fabrication

Using the hand lay-up method, we performed the composite fabrication process. The specimen design and preparation followed the standards for tensile testing, ASTM D-3039. The steps were as follows: Abaca fibers were immersed in a 5% NaOH solution for 2 hours, then dried in sunlight. Once it is dried, the fibers were cut to match the mold dimensions, with the fiber orientations arranged as parallel, random, or woven.

A glass mold with dimensions of 20 cm in length, 10 cm in width, and 0.5 cm in thickness was prepared. Mirror glaze applied to the mold to facilitate the removal of the composite specimen after drying. Polyester resin was mixed with a catalyst to accelerate the drying process, with the catalyst amounting to 1% of the total resin weight. The liquid resin, serving as the matrix, was poured into the mold, ensuring an even distribution.

The mold was then covered with a glass sheet, and pressure was applied by placing weights on top of the mold as a pressing tool. The drying process was conducted for 5–10 hours or longer if the composite was not cured. After curing, the composite was removed from the mold using a knife or cutter and cut into specimens for tensile testing.

2.3 Research Procedure Flowchart

The research procedure is illustrated in Figure 1.

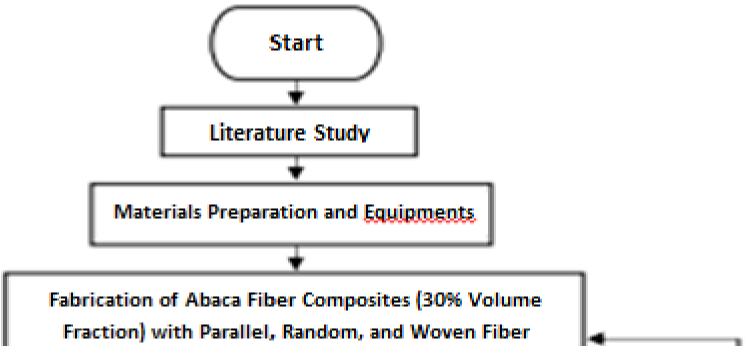


Figure 1 Research Flowchart

3. Result and Discussion

3.1 Tensile Test Specimens

The tensile test specimens consisted of 15 samples, with 5 specimens for each variation of fiber orientation, following the ASTM D-3039 standard. The specimens are shown in Figure 2.

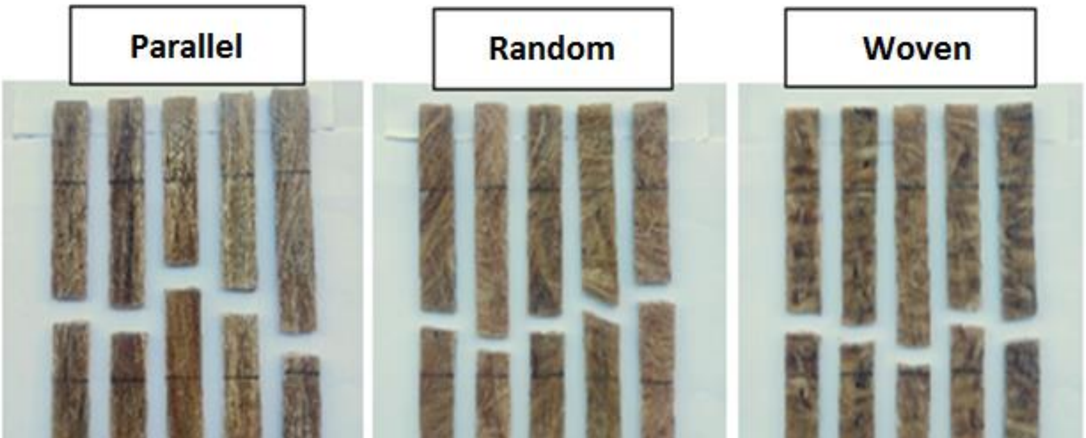
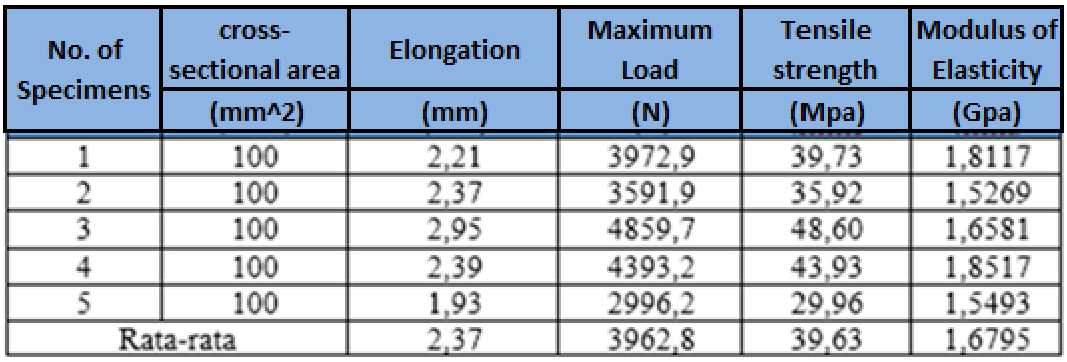


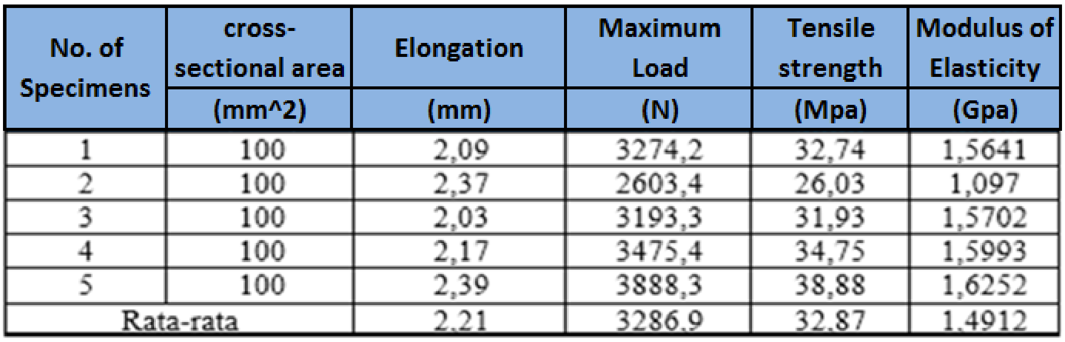
Figure 2 Tensile Test Specimens

The tensile tests based on ASTM D-3039 were conducted on abaca fiber-reinforced polyester composites treated with an alkali solution (5% NaOH) and a fiber volume fraction of 30%, using three different fiber orientations: parallel, random, and woven. To facilitate data analysis, the results are presented in tabular form, as shown in Table 1.



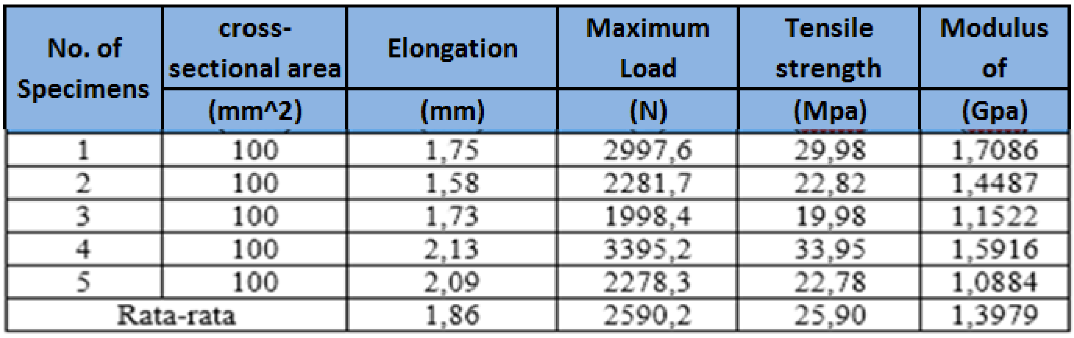
No. of Specimens	cross-sectional area	Elongation	Maximum Load	Tensile strength	Modulus of Elasticity
	(mm^2)	(mm)	(N)	(Mpa)	(Gpa)
1	100	2,21	3972,9	39,73	1,8117
2	100	2,37	3591,9	35,92	1,5269
3	100	2,95	4859,7	48,60	1,6581
4	100	2,39	4393,2	43,93	1,8517
5	100	1,93	2996,2	29,96	1,5493
Rata-rata		2,37	3962,8	39,63	1,6795

For the parallel fiber orientation, the results indicated that the minimum tensile strength was 29,96 MPa, shown by the fifth specimen with corresponding maximum load and modulus of elasticity of 2996,2 N and 1,5493 GPa, respectively. The highest tensile strength was 48,60 MPa shown by the third specimen with corresponding maximum load and modulus of elasticity of 4859,7 N and 1,6581 GPa, respectively. Table 2 provides the tensile test results for the random fiber orientation.



No. of Specimens	cross-sectional area	Elongation	Maximum Load	Tensile strength	Modulus of Elasticity
	(mm^2)	(mm)	(N)	(Mpa)	(Gpa)
1	100	2,09	3274,2	32,74	1,5641
2	100	2,37	2603,4	26,03	1,097
3	100	2,03	3193,3	31,93	1,5702
4	100	2,17	3475,4	34,75	1,5993
5	100	2,39	3888,3	38,88	1,6252
Rata-rata		2,21	3286,9	32,87	1,4912

For the random fiber orientation, the tensile strength indicated the lowest point at specimen 2 with 26,03 MPa and the maximum load was 2603,4 N. The highest level was 38,88 MPa, shown by specimen 5, with maximum loads of 3888,3 N. The modulus of elasticity ranged from 1,097 GPa to 1,6252 GPa, respectively. Table 3 presents the tensile test results for the woven fiber orientation.



No. of Specimens	cross-sectional area	Elongation	Maximum Load	Tensile strength	Modulus of
	(mm^2)	(mm)	(N)	(Mpa)	(Gpa)
1	100	1,75	2997,6	29,98	1,7086
2	100	1,58	2281,7	22,82	1,4487
3	100	1,73	1998,4	19,98	1,1522
4	100	2,13	3395,2	33,95	1,5916
5	100	2,09	2278,3	22,78	1,0884
Rata-rata		1,86	2590,2	25,90	1,3979

For the woven fiber orientation, the tensile strength ranged from 19,98 MPa (specimen 3) to 33,95 MPa (specimen 4), with maximum loads of 1998,4 N and 3395,2 N, respectively. The modulus of elasticity varied between 1,1522 GPa and 1,5916 GPa.

3.2 Comparison of Average Tensile Strength Based on Fiber Orientation

The differences in tensile strength can be attributed to factors such as fiber orientation, fiber volume fraction, and the bonding capability of the matrix. A comparison of the average tensile strength for the three fiber orientations (parallel, random, and woven) is shown in Figure 3.

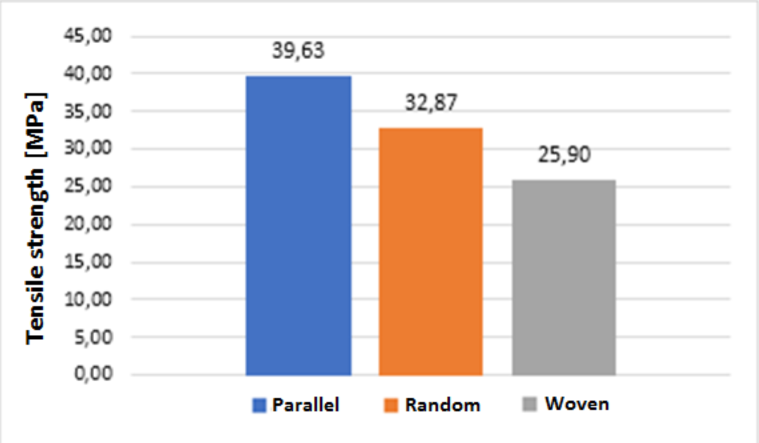


Figure 3 Comparison Diagram of Average Tensile Strength

The results indicate that the parallel fiber orientation exhibited the highest average tensile strength of 39,63 MPa. The random fiber orientation showed an average tensile strength of 32,87 MPa, while the woven orientation yielded the lowest average tensile strength of 25,90 MPa. A comparison of the average elongation values for the different fiber orientations is shown in Figure 4.

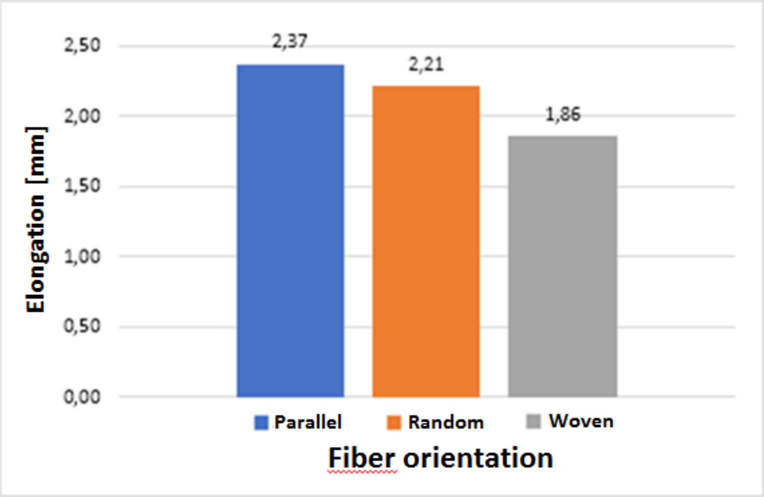


Figure 4 Comparison Diagram of Average Elongation Values

The figure 4 indicated that the parallel fiber orientation had the highest average elongation at 2,37 mm, followed by the random orientation at 2,21 mm, and the woven orientation at 1,86 mm. A comparison of the average Modulus of Elasticity for the three fiber orientations (parallel, random, and woven) is shown in Figure 5.

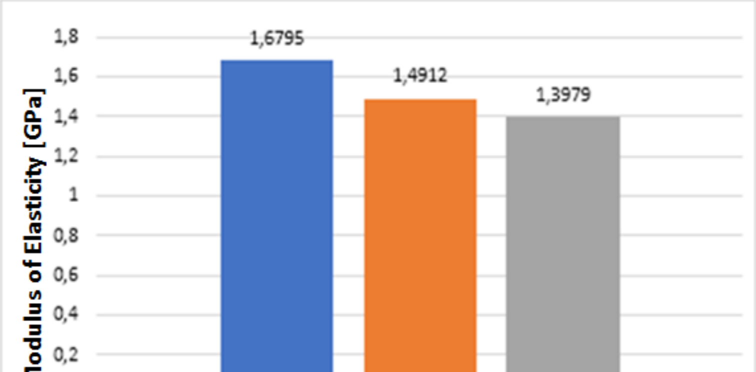


Figure 5 Comparison Diagram of Average Modulus of Elasticity Values

Figure 5 presents the comparison of the average modulus of elasticity for the three fiber orientations. The parallel orientation showed the highest modulus of elasticity at 1,6795 GPa, followed by the random orientation at 1,4912 GPa, and the woven orientation at 1,3979 GPa.

3.3 Macrography Analysis

Macrography analysis was conducted to examine the fracture surfaces of the tested specimens. The macro images, captured using a digital camera with up to 50× magnification at a resolution of 1280 × 960 pixels, were used to identify the type of fracture. For the parallel fiber orientation (Figure 6), the dominant fracture mode was brittle, with significant fiber pull-out observed. This indicates weak bonding between the fibers and the matrix, and the presence of voids around the fibers further contributed to the fractures.

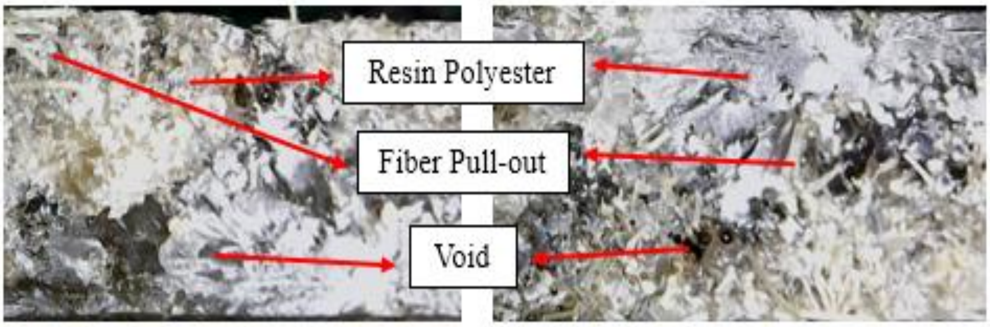


Figure 6 Macrography Analysis for the parallel fiber orientation

For the random fiber orientation (Figure 7), the fractures were primarily due to the brittle nature of the matrix. Additionally, voids trapped within the hardened resin caused weaknesses that made the specimens more susceptible to failure.

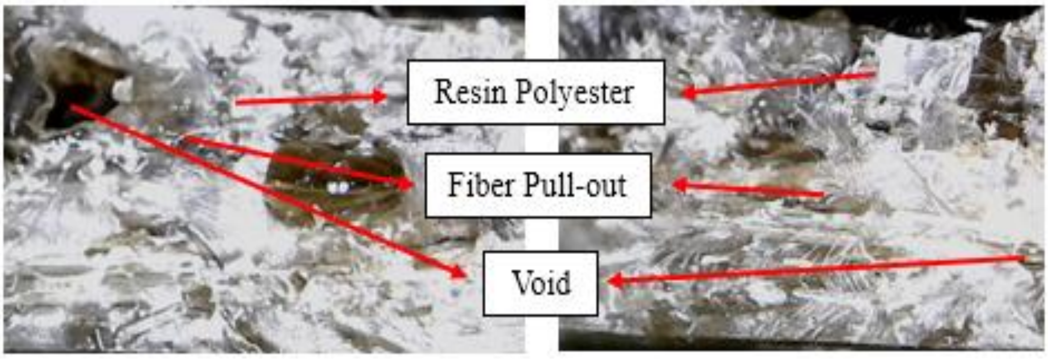


Figure 7 Macrography Analysis for the random fiber orientation

For the woven fiber orientation (Figure 8), the fractures observed were also brittle. Unlike the other orientations, there was minimal fiber pull-out, suggesting that the fibers played a limited role in resisting sudden loads.

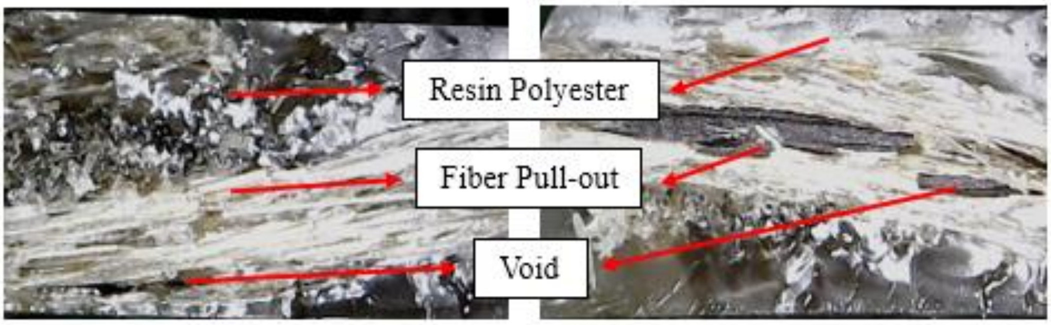


Figure 8 Macrography Analysis for the woven fiber orientation

These results emphasize the influence of fiber orientation on the mechanical properties of abaca fiber-reinforced composites. The parallel orientation provided superior tensile strength and modulus of elasticity, whereas the woven orientation showed the lowest performance.

4. Conclusion

Based on the results of the research, the following conclusions can be drawn: 1. This study found that fiber orientation affects the tensile strength of abaca fiber-reinforced polyester composites. Composites with parallel fiber orientation exhibited the highest tensile strength, followed by those with random and woven orientations. The tensile strength varied with fiber orientation. Parallel fibers showed the highest strength at 39,63 MPa, followed by random fibers at 32,87 MPa, and lastly woven fibers at 25,90 MPa.

2. Macrography analysis revealed that the fracture types observed were brittle fractures, with uneven fracture surfaces. Fiber pull-out was clear, showing that the fibers detached from the specimen because of weak bonding between the matrix and fibers. The fractures were also attributed to voids near the fibers.

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