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Investigation of Design Properties of Hybrid Fiber Polyester Matrix Composite

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Abstract

This study centered on experimental investigation of mechanical properties of bamboo/plantain fiber hybrid reinforced polymer matrix composite. A fiberglass single-cavity mold was used to produce hybrid bamboo-plantain fiber composites through a sandwich construction process. Fibers were cleaned, treated with 5% NaOH, and layered with resin in varied orientations within the wax-prepared mold. Curing at room temperature ensured bonding. Mechanical testing followed ASTM standards, examining tensile, impact, fatigue, and buckling properties. Tensile testing measured strength, impact testing assessed fracture characteristics, fatigue testing evaluated durability under cyclic loads, and buckling tests studied structural stability under compressive stress. Mechanical tests on HBPFC samples show that impact, tensile, fatigue, and buckling strengths vary by fiber orientation and volume in the composite. In impact tests, sample D1 had the highest resistance (24KJ/m²) and F1 the lowest (12KJ/m²). Tensile tests showed D1 with the highest strength (170N/mm²), while E1 had the lowest (135N/mm²). Fatigue tests indicated B2/D1 had maximum strength (165N/mm²) and A2/E1 the lowest (135N/mm²). In buckling tests, D1 was strongest (140N/mm²)) and C3/E1 weakest (80N/mm²)). In conclusion, the HBPFC testing determined key mechanical properties, showing sample D1 with the highest impact resistance and highest tensile strength. Recommendations include optimizing fiber ratios, collaborating with regulatory bodies for standards in marine applications, and researching production scale-up to maintain quality consistency.

Keywords: Banana fiber, plantain fiber, composites, reinforced polymer, mechanical properties.

1. Introduction

The increasing demand for eco-friendly materials has led to the exploration of natural fibers as reinforcement in polymer composites. These developments have sped up the development of more creative uses of bio-fibers as reinforcements in plastics, which are starting to replace conventional composite, metallic, and wood structures (Fuqua et al., 2012). Also, investigations have shown that hybridization of fiber in composite formulation improves impact strength, tensile, flexural and fatigue strength in the composites (Girishaet al., 2012; 2013; Patnaik et al., 2010; Rao et al., 2010; Sekaran et al., 2015; Venkateswaran et al., 2011; Venkateshwaran et al., 2012).

Bamboo and plantain fibers are abundant and renewable resources, making them ideal candidates for sustainable material development(Khalil et al., 2012; Patil, 2017). Bamboo fibers are known for their high strength-to-weight ratio, flexibility, and biodegradability. They offer excellent tensile strength and are relatively easy to process(Xu et al., 2023). While Plantain fibers are derived from the pseudo-stem of the plant. They arelightweight, have good tensile properties, and resist to wear(Adeniyi et al., 2019; Ihueze and Okafor, 2014).

Ramesh et al. (2013) investigated the mechanical properties of sisal, jute and glass fiber reinforced polyester composites. They observed that the addition of glass fiber into jute fiber composite resulted in maximum tensile strength. In the same way, they have observed that the jute and sisal mixture composites sample is capable of having maximum flexural strength and maximum impact strength was obtained for the sisal fiber composite.

Alavudeen et al. (2015) studied the mechanical properties of woven banana fiber, kenaf fiber and banana/kenaf hybrid fiber composites. The mechanical strength of woven banana/kenaf fiber hybrid composites increases due to the hybridization of kenaf with banana fibers. Tensile, flexural and impact strengths of the woven hybrid composite of banana/kenaf fibers are superior to those of the individual fibers. Sodium lauryl sulfate (SLS) treatments appear to provide additional improvement in mechanical strength through enhanced interfacial bonding. Morphological studies of fractured mechanical testing samples were performed by scanning electron microscopy (SEM) to understand the de-bonding of fiber/matrix adhesion.

Literatures on the influence of fillers on the mechanical properties of composite materials includes, Madhukiran, Rao and Madhusudan (2013) who studied banana/pineapple fibers hybrid composites prepared for 0/40, 15/25, 20/20, 25/15, and 40/0 weight fraction ratios, while overall fiber content was fixed as 40 wt%. Hybrid composites showed higher flexural strength than the monofiber reinforced composites. The banana/pineapple hybrid composite with weight fraction of 25/15 showed maximum flexural strength, flexural modulus, and maximum interlaminar shear strength.

Combining bamboo and plantain fibers can leverage the strengths of both materials, leading to composites with enhanced properties. No previous study to the best authors' knowledge and through search in peer-reviewed databases has experimentally explored the mechanical behavior of hybrid plantain/bamboo fiber polyester composite in an academic setting. However, researches have shown that plantain fiber reinforcement and bamboo fiber reinforcement have good mechanical properties. However, there is a need to systematically investigate the mechanical performance of hybrid bamboo/plantain fiber reinforced polymer composites to determine their viability as a substitute for conventional materials. This study aims to explore the optimal combination of fiber orientation, volume fraction, and stress ratio to enhance the mechanical properties of these composites, addressing the gap in knowledge regarding their application in high-performance engineering sectors

2.0 Material and methods

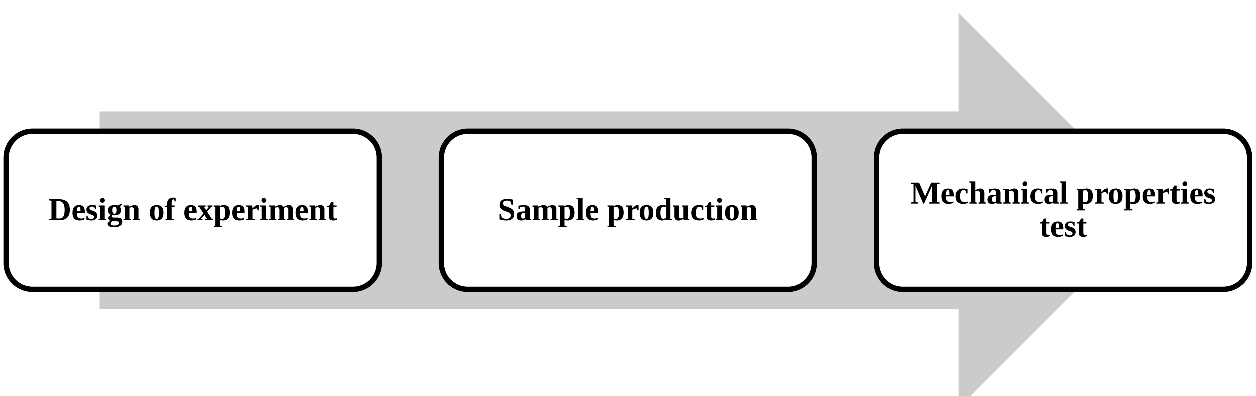

Figure 1: Process chart

2.1 Design of experiment

The design employs a standard random optimal (custom) design with the DESIGN EXPERT SOFTWARE 13. The design was augmented with an axial blend check and the overall centroid. The vertices and overall centroid were not replicated, reducing the experiment size to 22 blends total. Table 1 below shows the experiment formulation generated with the software which served as a guide for the development of the samples.

Table 1: experiment formulation

Samples		**Factor 1**	**Factor 2**	**Factor 3**	**Response 1**	**Response 2**	**Response 3**	**Response 4**
	Run	A: Orientation	B: Vol. Fraction	C: Stress Ratio	Impact Test	Ultimate Tensile Strength	Fatigue Strength	Buckling load (critical stress)
		Degrees	%		(kJ/m^2)	N/mm^2	N/mm^2	N/mm^2
F1	1	60	60	-1				
C1	2	60	60	-0.25				
A2	3	30	30	-1				
B2	4	0	0	-1				
A1	5	60	60	0.5				
E2	6	60	60	-1				
A2	7	30	30	-1				
C3	8	30	30	-0.25				
B1	9	30	30	-0.25				
B3	10	0	0	-0.25				
D3	11	0	0	0.5				
E1	12	30	30	-1				
C2	13	0	0	-0.25				
F2	14	0	0	-1				
D2	15	30	30	0.5				
A3	16	0	0	0.5				
D1	17	60	60	0.5				
E3	18	60	60	-0.25				
A3	19	0	0	0.5				
A2	20	30	30	-1				
B1	21	30	30	-0.25				
A1	22	60	60	0.5				

Factor 1: Orientation (Degrees)

Levels: 0, 30, 60

This factor examines the angle of fiber orientation in the composite, which can significantly affect mechanical properties.

Factor 2: Volume Fraction (%)

Levels: 40, 50, 60

This represents the percentage of fibers within the composite. Varying the volume fraction can influence strength and stiffness.

Factor 3: Stress Ratio

Levels: -1, -0.25, 0.5

The stress ratio impacts how the composite handles different loading conditions, affecting its fatigue strength and durability.

2.2 Sample production

The mold used is a simple, single cavity mold made of fiberglass composite. The sample production process involves the layer-by-layer placement of the matted plantain-bamboo fiber and was repeated until the number of samples needed is completed. This is known as sandwich construction. The process involves;

i. Fiber Preparation: Fibers from bamboo and plantain are gathered, washed to remove dirt and impurities and air-dried to reduce moisture content.
ii. Fiber Treatment (Alkali Treatment): The fibers are soaked in a 5% NaOH solution for 4-6 hours, rinsed thoroughly with water to remove residual chemicals, and dried completely.
iii. Composite Fabrication: Using the Lay-Up Process, the fiberglass mold is prepared by cleaning and applying wax using a spray gun for a high-quality surface. When the wax coat has cured sufficiently, fibers are manually placed in the desired orientation (i.e. 0°, 30°, 60°) within the mold. The laminating resin is applied over the fiber layers using a brush and roller, the roller is used to consolidate the laminate, thoroughly wetting the reinforcement and removing entrapped air.
Subsequent layers of bamboo and plantain fibers are added to build laminate thickness based on the design ensuring even distribution of fibers to avoid weak spots.
iv. Curing Process: The composite is cured for 24 hours at room temperature to ensure proper bonding.

2.3 Mechanical properties testing

Mechanical properties depend on the testing conditions such as temperature, load and strain amount. The hybrid FRP composites will be tested for mechanical characterization (tensile, fatigue, and impact). All tests was carried out by using international standards such as ASTM standards.

2.3.1 Impact Tests

The composite's fracture properties were assessed using a Charpy impact tester (Changteh China, model JC-25, pendulum capacity of 4J at a test velocity of 5 m/s). The impact energy of the composite is measured using this technique. A pendulum with a large striking edge is permitted to strike the specimen during this test. The hammer's potential energy is determined by its mass and drop height. There are two steps involved in breaking the sample. A fracture requires energy to form, and it takes even more energy to widen to the point of failure. To increase the reproducibility of the mechanism of failure, the specimen is notched at 2.5mm depth. The ASTM D256 was used to conduct the impact test.

2.3.2 Tensile Tests

Tensile tests are applied to observe the strength of the laminate hybrid FRP composites. A dog bone-shaped specimen prepared according to international standards (ASTM: D638) is used. The study involved deforming a sample with increasing tensile load, plotting the force-extension curve, and determining the ultimate tensile strength and elastic modulus. Tests were conducted using a universal tensile testing machine with a capacity of 1-20 KN and a 5KN applied load.

2.3.3 Fatigue Tests

In this research, the fatigue test was carried out with SM1090V (TecQuipment, Nottingham, UK) with a data acquisition system for real-time data capture, monitoring and display by using the ASTM D3479 method. This machine uses a motor to rotate a circular cantilever specimen under alternating stresses, demonstrating fatigue failure using a self-aligning bearing inside a gimbal. The machine repeatedly stresses the specimen for a known number of cycles, causing alternate compressive and tensile stress on any part along the unsupported length. The applied stress on the specimen is described with a sinusoidal function, ensuring repeatability and accuracy in testing.

2.3.4 Buckling Tests

Buckling test assesses the compressive strength and stiffness properties of polymer matrix composite materials. An Instron 8801 (Instron, Norwood, MA, USA) model machine was used to conduct the buckling test under axial compression (ASTM D695). Test samples machined from the formed HBPFC were used for the experimental buckling test. The critical buckling load of the composites is discovered from the load versus the displacement curves.

3.0 Results and Discussions

The results of the mechanical properties test conducted on the HBPFC test samples are presented in graphs below from Figure 2 – Figure 5. The results show the ultimate tensile, impact, fatigue strength and buckling strength of the material developed.

3.1 Impact test

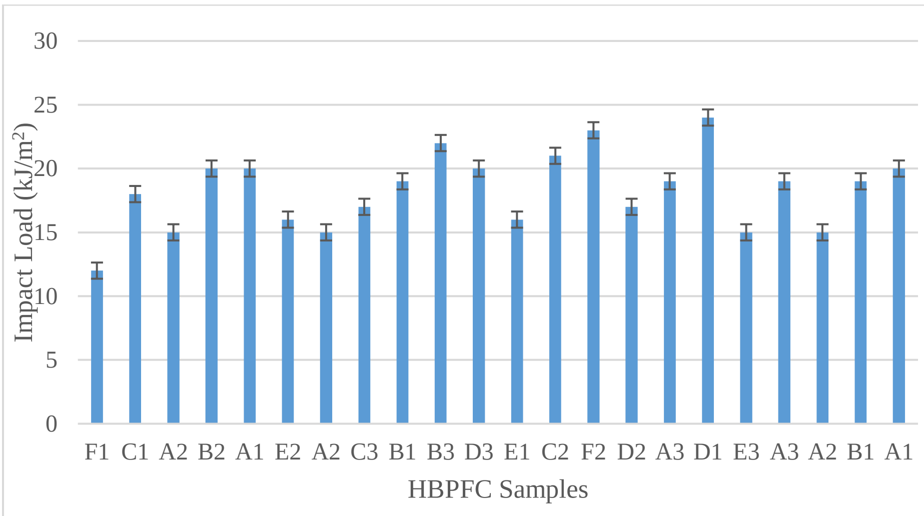

Figure 2: Impact Load Results vs HBPFC Sample

Fig 2 illustrates the impact test results of the HBPFC test samples investigated. The result shows that the sample with the highest impact resistance is sample D1 having a value of 24kJ/m² and sample F1 has the lowest tensile strength value of 12kJ/m². In respect of the test result, it is observed that impact resistance is influenced by the orientation of the fibre and the increase of fiber volume in the polymer matrix composite.

3.2 Tensile test

Fig 3 presents the tensile strength results of the HBPFC test samples investigated. From the result, it can be concluded that the sample with the highest tensile strength is sample D1 having a value of 170N/mm² while sample E1 has the lowest ultimate tensile strength value of 135N/mm². However, from the result of the test, it is observed that tensile strength is affected by the orientation of the fiber and the increase of fiber volume in the polymer matrix composite.

Fig 4 shows the fatigue test results of the HBPFC test samples investigated. The result shows that the sample with the highest fatigue strength is sample B2/D1 having a value of 165N/mm² and sample A2/E1 has the lowest fatigue strength value of 135N/mm². In respect of the test result, it is observed that fatigue is influenced by the orientation of the fiber and the increase of fiber volume in the polymer matrix composite.

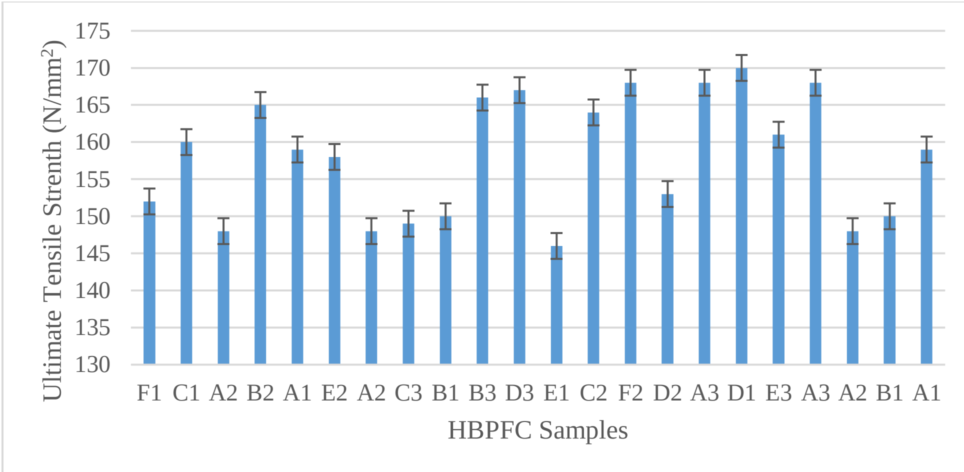

Figure 3: Tensile Strength vs HBPFC Sample

3.3 Fatigue test

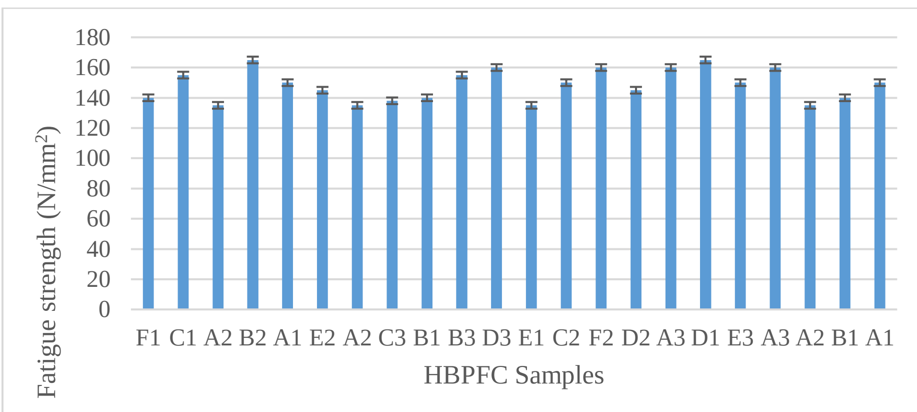

Figure 4: Fatigue Strength vs HBPFC Sample

3.4 Buckling test

Fig 5 shows the buckling test results of the HBPFC test samples investigated. The result shows that the sample with the highest fatigue strength is sample D1 having a value of 140N/mm^2 and sample C3/E1 has the lowest buckling load value of 80N/mm^2. For the test result, it is observed that the resistance to buckling load is influenced by the orientation of the fiber and the increase of fiber volume in the polymer matrix composite.

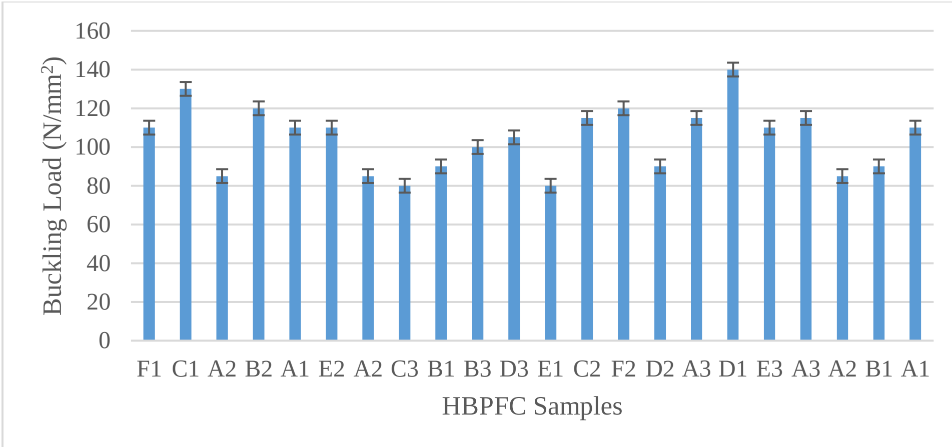

Figure 5: Buckling Load vs HBPFC Sample

4.0 Conclusion

This investigation was able to ascertain the various mechanical properties which were obtained by the HBPFC testing. These test results showed that the sample with the highest impact resistance is sample D1 having a value of 24kJ/m^2 and sample F1 has the lowest impact value of 12kJ/m^2. Also, it can be concluded that the sample with the highest ultimate tensile strength is sample D1 having a value of 170N/mm^2 while sample E1 has the lowest ultimate tensile strength value of 135N/mm^2. The result shows that the sample with the highest fatigue strength is samples B2/D1 having a value of 165N/mm^2 and sample A2/E1 has the lowest fatigue strength value of 135N/mm^2. The result shows that the sample with the highest buckling strength is sample D1 having a value of 140N/mm^2 and sample C3/E1 has the lowest buckling strength value of 80N/mm^2.

5.0 Recommendations

i. Hybrid Fiber Optimization: Further inquiry into various ratios and configurations of plantain and bamboo fibers may result in composites with even more enhanced attributes tailored for specific applications.
ii. Regulatory Compliance: Collaborative initiatives with regulatory authorities are essential to establish standards and certifications pertinent to the utilization of this innovative composite in marine applications.
iii. Scaling Up Production: The transition from laboratory-scale production to industrial-scale manufacturing introduces complexities in the maintenance of consistent quality and properties. Additional research is warranted to optimize production processes at a larger scale.

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