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Investigation of Mechanical Properties in Ligno-Cellulosic Fiber-Reinforced Polymer Composites with SiC and Al_2O_3 Fillers[1]

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Abstract

This study investigates the influence of fiber loading and filler content on the tensile properties of epoxy composites reinforced with a lignocellulose fiber i.e. banana fiber. Natural fiber composites have risen to popularity in engineering applications due to their ability to optimize strength, weight, and cost as the world moves toward eco-friendly materials. Banana fiber, which is derived from the pseudostems of ripe bananas, is a readily available reinforcing option. Both unfilled and filled composites containing silicon carbide (SiC) and aluminum oxide (Al2O3) are the subject of this study. Results show that unfilled composites are sensitive to fiber loading in terms of tensile strength, flexural strength, and hardness. An optimum fiber loading of 15% by weight demonstrates the highest tensile and flexural strengths. Additionally, there is a pattern whereby increasing the filler content from 0 to 20 wt. percent increases the tensile and flexural strengths, followed by a decrease at 30 wt. percent. Surprisingly, the increased flexural and tensile strengths are mostly attributable to the 20 wt.% Al2O3 concentration. This study highlights the potential for improving composite performance by tuning the fiber-to-filler ratio, a step forward in the development of environmentally friendly materials. This research adds to the growing body of evidence supporting the usage of sustainable engineering materials in today's environmentally conscious world.

Keywords

Banana Fiber, Epoxy, Mechanical Behavior, SiC, Al_2O_3.

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Introduction

Heightened global environmental awareness has spurred the search for renewable materials with both ecological benefits and economic promise. In response, natural fiber composites have gained traction in diverse engineering applications, adeptly bolstering strength while optimizing weight and cost factors. This progressive approach involves harnessing natural fibers as reinforcement elements within composites, a strategy that has recently gained momentum in pursuit of high-performance, efficient engineering materials. Against this backdrop, the rich cultivation of bananas in India offers a unique opportunity to harness banana fiber, a readily available resource sourced from the pseudostems post-fruit utilization. Researchers have actively explored the impact of various factors, including fiber types and diverse filler materials, on the mechanical and physical attributes of fabricated fiber-reinforced composites. These studies have employed statistical methodologies and computational techniques to unravel the intricate relationships shaping these material properties [1,2,3]. For instance, the work by Pothan et al. [4] delves into the viscoelastic properties of polyester in conjunction with banana fiber, revealing the significant influence of factors such as fiber content, temperature, and frequency on the composite's behavior. Pothan et al. [5] studied jute, sisal, and coir-reinforced polyester composites with banana fibers. Water retention increased with fiber content. Tensile strength peaked at 30 mm fiber length, while 40 mm fiber length yielded optimal impact strength. Banana fiber composites displayed superior mechanical properties compared to others. Similarly, Khalil et al. [6] undertook an insightful analysis of the fine structure of banana and pineapple fibers through SEM, offering insights into chemical compositions and their implications for reducing environmental risks tied to plant waste disposal. Furthermore, investigations into coconut coir, Jamaican banana, and bagasse fiber by Nilza et al. [7] demonstrated the intriguing diversity in composite materials derived from various natural Jamaican cellulose fibers. Tensile strength, carbon content, and chemical analysis revealed distinct attributes of different fibers, with banana fiber emerging as a standout in terms of heightened carbon and cellulose content, tensile strength, and hardness in comparison to other natural fiber composites. In a different vein, Idicula et al. [8,9] delved into the mechanical behavior of banana, sisal, and hybrid reinforced polyester composites, focusing on their tensile properties and guiding the design of optimal layering patterns and fiber arrangements. Moreover, Chattopadhyay et al. [10] explored composites incorporating polypropylene, capitalizing on the biodegradability of banana, bamboo, and pineapple leaf fiber reinforcements. This strategy aligns with environmental goals, diminishing reliance on non-biodegradable polymers and reducing polymer content to tackle waste issues. In continuation, Amir et al. [11] probed the effects of different banana fiber types and loading percentages on the mechanical attributes of high-performance polypropylene composites, incorporating maleic anhydride to enhance polymer-fiber bonding. Notably, the use of banana fiber yarn in polypropylene composite fabrication showcased superior results. Sunil et al. [12] analyzed banana fiber-reinforced polylactic acid composites with varying banana/PLA weight percentages, improving mechanical properties through chemical treatment. Merlini et al. [13] studied polyurethane-reinforced composites with alkali-treated banana fibers. Chemical treatment with NaOH improved fiber length, tensile properties, and interfacial adhesion, resulting in enhanced composite tensile strength. Singh et al. [14] investigated the flexibility and impact resistance of banana fiber composites, finding that adding silica powder increased both the modulus of elasticity and impact strength. This article subsequently presents a comparative study examining the mechanical properties of unfilled and SiC and Al_2O_3-filled banana fiber-reinforced polymer composites. Through insightful investigation, the study adds to the growing body of knowledge, shedding light on strategies for enhancing composite performance and contributing to the broader mission of advancing sustainable engineering solutions.

2. Materials and Methodology

2.1 Material

The matrix material selected for the construction of banana fiber composites was LY556 resin, which was purchased from ASES Chemical Works in the Jodhpur Industrial Estate. The thermosetting polymeric epoxy resin known as LY556 resin is well known for its extensive use. A precise weight ratio of 10:100 was followed when LY556 and HY951 Hardener, both supplied by ASES Chemical Works, were combined. Due to the resin's beneficial characteristics, which include corrosion resistance, mechanical toughness, minimum shrinkage, and admirable chemical qualities, this particular blend was chosen. Given these inherent advantages, the polymeric epoxy resin, which is widely used in many composite formations and has a strong track record of effectiveness, was chosen for the current endeavour. The nonwoven banana fiber and chopped nonwoven banana fiber used in the current investigation are shown in Figure 1. These fibers have superior mechanical characteristics to glass fiber [15,16,17].

FIG.1. Nonwoven and chopped nonwoven banana fiber

2.2 Methodology:

The fabrication of the banana fiber composites required numerous crucial phases during the experimental process. Seven wooden blocks were first prepared as per Tables I and II, and the bottom of the mould plate was covered with a thin plastic sheet to achieve the best possible surface finish. To avoid any adhesion between the polymer and the sheet after the release, a layer of gel silicon spray was placed on the surface of the plastic sheet. The preparation of banana fiber was the following step, which involved carefully chopping the fibers into tiny pieces and weighing them in accordance with the specified ratio. The weighted banana fiber fragments were then combined in the appropriate ratios with epoxy resin and the prescribed hardener. It is noteworthy that silicon carbide and aluminum oxide were not included in this phase. The epoxy resin was completely combined with the fiber and hardener before being put onto the ready-made wooden block. The plastic sheet was placed on top of the fiber-polymer layer after being treated with a releasing gel on its inner surface. The plastic sheet was gently rolled under a roller to remove any surplus polymer and trapped air. Finally, a weight was placed on the composite, and it was given 24 hours to cure [18,19].

TABLE I. Composites fabricated without filler

Composite Designation	Amount of material (wt.%)		
	Fiber	Matrix	Filler
Banana Epoxy (BE10)	10	90	0
Banana Epoxy (BE15)	15	85	0
Banana Epoxy (BE20)	20	80	0

TABLE II. Composites fabricated with filler

Composite Designation	Amount of material (wt.%)			
	Fiber	Matrix	SiC	Al_2O_3
10% SiC-filled Banana Epoxy (10SBE15)	15	75	10	0
20 % SiC-filled Banana Epoxy (20SBE15)	15	65	20	0
30% SiC-filled Banana Epoxy (30SBE15)	15	55	30	0
10% Al_2O_3-filled Banana Epoxy (10ABE15)	15	75	0	10
20 % Al_2O_3-filled Banana Epoxy (20ABE15)	15	65	0	20
30% Al_2O_3-filled Banana Epoxy (30ABE15)	15	55	0	30

2.3 Mechanical Testing:

To ease later mechanical testing, a variety of specimens were created once the composites were created in accordance with ASTM requirements. Using the Instron 1195 universal testing apparatus and adhering to ASTM D3039-76 guidelines, the tensile test was performed. The test used flat specimens, including dog-bone-shaped specimens and straight-side types with end tabs to which uniaxial stress was given from both ends. The samples as shown in figure 2 followed the guidelines of 200 mm by 10 mm with a crosshead speed of 10 mm per minute.

FIG.2. Tensile test specimens

The Instron 1195 testing apparatus was used in a three-point bend test configuration for the flexural strength evaluation, which was carried out at room temperature. The purpose of this setup was to ascertain inter-laminar shear failure. According to standard testing protocols, specimens with dimensions of 100 mm x 10 mm as illustrated in figure 3 had thicknesses that varied depending on the type of composite.

FIG.3. Flexural test specimens

Additionally, using Rockwell cum Brinell hardness tester equipment, Rockwell hardness measurements were made in accordance with the ASTM: E-18 standard. All of the specimens in Figure 3 were subjected to minor and large loads, 10 kgf and 150 kgf, respectively, for the evaluations. This extensive testing approach was carried out to thoroughly assess the mechanical characteristics of the created composites made of banana fibers [20,21,22].

FIG.4. Hardness test specimens

3. Results and Discussions

3.1. Unfilled banana fiber-reinforced composites

3.1.1 Tensile Test

The Instron 1195 universal testing apparatus was used to conduct tensile tests on the manufactured composites in ambient lighting. The specimens' dimensions for the tensile testing were in accordance with the ASTM standard (D3039-76). A tensile load was applied to the samples with a crosshead speed of 10 mm/min. Two identical test specimens were used for each manufactured composite. According to Table III, the obtained tensile strength's average value was regarded as the composite in question's representative tensile strength. Figure 5 displays a bar graph of the tensile strength of composites made from unfilled banana fibers. The study of Figure 1 reveals a clear pattern: when fiber loading is increased, the tensile strength of the manufactured composites increases. Because the fiber interface area is only partially covered, the tensile strength is still weak at smaller weight loading percentages like BE10. The fiber interface area extends as the weight percentage of fiber rises, as seen in BE15, which causes a corresponding rise in tensile strength. However as demonstrated by BE20, going over a certain point causes the tensile strength to drop. This reduction can be due to imperfect adhesion throughout the full surface of the composite, which results from fiber interactions and insufficient fiber wetting [23,24,25]. Surprisingly, among all the manufactured banana fiber-reinforced composites without any filler materials, the composite with 15% fiber loading (BE15) emerges as the winner, displaying the highest tensile strength.

TABLE III. Tensile strength of unfilled composites

Composites	Fiber (wt.%)	Tensile Strength (MPa)		
		1	2	Mean
BE10	10	6.5	6.1	6.3

BE15	15	10.2	9.6	9.9
BE20	20	7.2	7.8	7.5

FIG. 5. Comparison of Tensile strength using different wt.% of Banana Fiber

3.1.2 Flexural Test

Using the universal testing apparatus, the composite underwent a flexural test (UTM Instron 1195). The specimens used in the flexural test were created in line with the ASTM standard (D2344-84), guaranteeing that they were the right size and shape. At a crosshead speed of 0.5 mm/min, the samples were subjected to a flexural load. Each manufactured composite was evaluated on two identical samples. As shown in Table IV, the flexural strength for that particular composite was calculated using the average value, which was then recorded. A bar graph showing the flexural strength of the composites made from unfilled banana fibers is also shown in the bar graph.

TABLE IV. Flexural strength of unfilled composites

Composites	Fiber (wt.%)	Flexural strength (MPa)		
		1	2	Mean
BE10	10	18.3	17.8	18.05
BE15	15	22.8	23.2	23
BE20	20	21.3	20.9	21.1

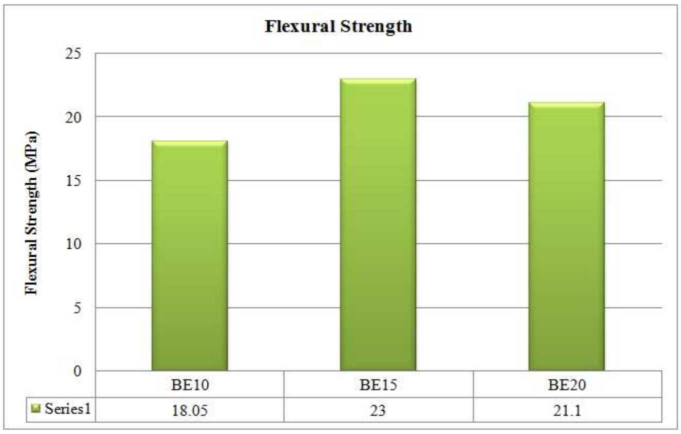

FIG. 6. Comparison of Flexural strength using different wt.% of Banana Fiber

Figure 6 shows that the flexural strength of produced composites increases with fiber loading up to 15%. (BE10–BE15). Higher fiber percentages limit polymer matrix phase slippage due to composites' more uniform fiber dispersion. This impact is affected by fibers near stress concentrations. Crack initiation and propagation in numerous directions improve flexural strength due to uniform fiber distribution [23,24,25]. Fiber loading decreases flexural strength after BE20. Insufficient fiber wetting and interactions reduce composite surface adherence. Flexural strength is strongest in 15%-loaded fibers. This shows how important composite fiber loading percentage is for mechanical performance.

3.1.3 Hardness

The hardness of a material has a substantial influence on its tribological behavior, making it critical to boost hardness for improved wear resistance. Table V summarises the hardness values, including the average value, for all composite variations.

TABLE V. Hardness of unfilled composites

Composites	Fiber (wt.%)	Hardness (HV)		
		1	2	Mean
BE10	10	23.6	23.2	23.4
BE15	15	24.2	24.4	24.3
BE20	20	20.5	19.8	20.15

Figure 7 depicts a bar chart demonstrating the hardness levels of unfilled banana fiber composites based on this data. Initially, an increase in the weight percentage of banana reinforcement, namely from 10% to 15%, increases the hardness of the produced unfilled composites (BE10, BE15, and BE20). This improvement can be attributed to enhanced stress distribution and increased indentation resistance within the matrix as a result of increased banana fiber loading [23,24,25]. However, adding banana fiber above the 15% threshold causes a decrease in hardness. The observed decrease in hardness is ascribed to a weakening of the connection between the matrix and the reinforcing elements.

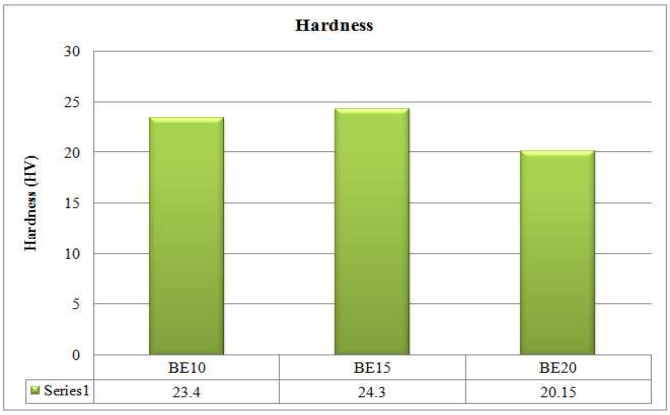

FIG. 7. Comparison of Hardness using different wt.% of Banana Fiber

3.2 SiC and Al_2O_3 Filled Banana fiber-reinforced composites

3.2.1 Tensile Test

All composites were tested with two identical specimens. The composite's average tensile strength is in Table VI. Figure 8 shows the corresponding tensile strengths. The curve shows that composite tensile strength increases with SiC or Al_2O_3 filler content up to 20% by weight. Stress distribution obstacles, such as filler particles, redirect stress, improving this. These filler particles also increase bonding amongst the three composite ingredients. Tensile strength decreases as filler particles exceed 20% of weight. The additional filler particles cover more surface area, leaving less matrix material for bonding. Insufficient or improper bonding between the three pieces affects composite stress distribution and tensile strength. Note that the composite with the best tensile strength has 20% filler (20ABE15).

TABLE VI. Tensile strength of SiC and Al2O3-filled banana fiber-reinforced composites

Composite Designation	Tensile Strength (MPa)		
	1	2	Mean
Banana Epoxy (BE15)	10.2	9.6	9.9
10% SiC-filled Banana Epoxy (10SBE15)	11.89	11.25	11.57
20 % SiC-filled Banana Epoxy (20SBE15)	19.64	17.82	18.73
30% SiC-filled Banana Epoxy (30SBE15)	12.88	13.54	13.21

10% Al_2O_3 -filled Banana Epoxy (10ABE15)	13.31	12.43	12.87
20 % Al_2O_3 -filled Banana Epoxy (20ABE15)	18.16	19.58	18.87
30% Al_2O_3 -filled Banana Epoxy (30ABE15)	17.36	14.34	15.85

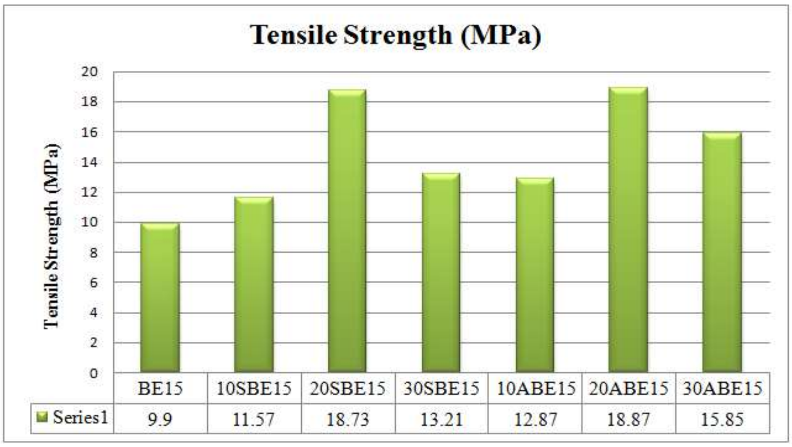

FIG. 8. Comparison of Tensile strength using different wt.% of SiC and Al_2O_3 filled Banana Fiber

3.2.2 Flexural Test

Each composite was examined with two identical specimens. The average flexural strength is in Table VII. The flexural strength values are shown in Figure 9. As demonstrated in the bar graph, the flexural strength of the composites increases with SiC or Al_2O_3 filler weight up to 20%. This improvement is due to the fiber, filler, and epoxy matrix bonding surface area. Further filler material above 20% weight decreases composite flexural strength. This reduction is due to incorrect fiber wetting causing surface adhesion issues. Thus, the alumina particles, fiber, and epoxy matrix have poor interfacial bonding. Notably, Al_2O_3 particles with 20% weight load maximise flexural strength.

TABLE VII. Flexural strength of SiC and Al_2O_3-filled banana fiber-reinforced composites

Composite Designation	Flexural Strength (MPa)		
	1	2	Mean
Banana Epoxy (BE15)	22.8	23.2	23
10% SiC-filled Banana Epoxy (10SBE15)	22.26	21.3	21.78
20 % SiC-filled Banana Epoxy (20SBE15)	45.47	46.27	45.87
30% SiC-filled Banana Epoxy (30SBE15)	38.65	37.85	38.25

10% Al_2O_3-filled Banana Epoxy (10ABE15)	23.11	25.63	24.37
20 % Al_2O_3-filled Banana Epoxy (20ABE15)	48.2	47.24	47.72
30% Al_2O_3-filled Banana Epoxy (30ABE15)	43.15	40.57	41.86

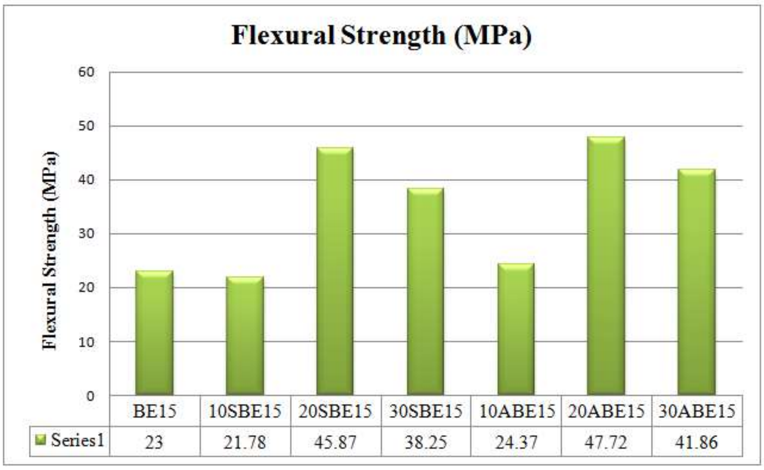

FIG. 9. Comparison of flexural strength using different wt.% of SiC and Al_2O_3 filled Banana Fiber

3.2.3 Hardness Test

Table VIII presents the hardness values of the fabricated composites, along with their respective averages for all banana fiber-reinforced composites. The accompanying bar chart in Figure 10 graphically depicts these average hardness values. Evident from both the tabulated data and the graphical representation, a distinct pattern emerges. It reveals that the hardness of the fabricated composites experiences an upward trajectory with an increase in the weight percentage of either SiC or Al_2O_3 particulates integrated into the composites.

TABLE VIII. Hardness of SiC and Al_2O_3-filled banana fiber-reinforced composites

Composite Designation	Hardness (HV)		
	1	2	Mean
Banana Epoxy (BE15)	24.2	24.4	24.3
10% SiC-filled Banana Epoxy (10SBE15)	32	32.8	32.4
20 % SiC-filled Banana Epoxy (20SBE15)	38.5	36.1	37.3
30% SiC-filled Banana Epoxy (30SBE15)	45.1	45.3	45.2
10% Al_2O_3-filled Banan Epoxy (10ABE15)	36.73	36.03	36.38

20 % Al_2O_3-filled Banana Epoxy (20ABE15)	40.32	42.22	41.27
30% Al_2O_3-filled Banana Epoxy (30ABE15)	52.4	50.06	51.23

FIG. 10. Comparison of hardness using different wt% of SiC and Al_2O_3 filled Banana Fiber

The 30ABE15 composite, with 30% Al2O3 particles, is the hardest. The increasing weight proportion of filler particles increases composite density, causing this phenomenon. The increase in composite hardness indicates a better matrix-reinforcing material bond.

4. Conclusion

This study focused on understanding how variations in fiber loading and filler content by weight percentage impact the tensile properties of banana fiber-reinforced epoxy composites. The investigation reveals that altering the weight percentage of banana fiber significantly influences the tensile strength, flexural strength, and hardness of unfilled banana reinforcement composites. A consistent trend emerges where these mechanical properties increase as fiber loading goes from 10 wt. % to 15 wt. %, but surpassing 15 wt. % leads to a decrease. The composite configuration BE 15 stands out with the highest mechanical properties among unfilled composites. When fillers are introduced, an initial increase in tensile and flexural strength up to 20 wt. % is noted due to stress distribution and bonding enhancement. However, beyond 20 wt.%, a decrease in tensile strength occurs due to incomplete adhesion. The composite with 20% wt. of Al_2O_3 filler excels in mechanical performance. A composite with 15 wt. % of banana fiber and 30 wt. % of Al_2O_3 particles achieves maximum hardness. This study illuminates the relationship between fiber, filler, and mechanical properties in composites and helps to develop innovative composite materials with improved mechanical properties by shedding light on sustainable engineering solutions.

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