STM JOURNALS

Journal of
Polymer & Composites

https://journals.stmjournals.com/jopc

ISSN: 2321-2810 (Online)
ISSN: 2321-8525 (Print)
Volume 14, Issue 5, 2026
September–October
DOI (Journal): 10.37591/JoPC

Research JoPC

Experimental Study on the Fabrication and Mechanical Properties of Natural Fiber Reinforced Polymer Hybrid Composites

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Abstract

Natural-fiber-reinforced polymer composites are increasingly investigated as lower-impact alternatives to conventional synthetic fiber systems. This work fabricated and mechanically characterized a sisal-coconut coir fiber-reinforced epoxy hybrid composite and compared its performance with a glass fiber-reinforced polymer (GFRP) epoxy composite under the reported laboratory conditions. The hybrid reinforcement contained 75% sisal fiber and 25% coconut coir fiber and was incorporated into an epoxy LY556/HY951 matrix by the hand lay-up technique. The laminate was cured at room temperature for approximately 24 h, cut to standard specimen dimensions, and tested in tension, flexure, and impact according to ASTM D3039, ASTM D790, and ASTM D6110, respectively. The sisal-coir hybrid composite exhibited an ultimate tensile strength of 186 MPa and a flexural strength of 313.78 MPa, compared with 94 MPa and 132.10 MPa, respectively, for the GFRP epoxy specimen. The average impact energy of the hybrid composite was 9.33 J, whereas the GFRP specimen absorbed 8.00 J. Under the specific fabrication and testing conditions reported, the hybrid composite, therefore, showed higher measured tensile, flexural, and impact performance than the GFRP comparator. The combined contribution of sisal to load bearing and coir to energy absorption provides a practical basis for further evaluation of this material in low- to medium-load-bearing applications. Additional replicate testing, statistical analysis, and durability characterization are required before broader structural substitution is established.

Keywords: Sisal fiber, coconut coir fiber, hybrid composite, epoxy resin, tensile strength

INTRODUCTION

Glass fiber-reinforced polymers (GFRPs) remain widely used because of their favorable mechanical performance and durability, but their non-biodegradable reinforcement and end-of-life challenges encourage the evaluation of renewable alternatives. Plant-derived fibers – such as sisal and coconut coir – offer low density, renewability, widespread availability, and useful specific mechanical properties. Hybridization is particularly attractive because it can combine the stiffness and tensile capability of one fiber with the toughness and energy-absorption characteristics of another.

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Received Date: August 29, 2026
Accepted Date: September 15, 2026
Published Date: September 21, 2026

Citation: S. D. Sathishkumar. Experimental Study on the Fabrication and Mechanical Properties of Natural Fiber Reinforced Polymer Hybrid Composites. Journal of Polymer & Composites. 2026; 14(5): 333–344p.

Recent studies support the use of hybrid natural-fiber architectures to obtain balanced mechanical properties. Cavalcanti et al. reported that sisal/flax intraply hybrids could retain competitive longitudinal performance while improving selected transverse and shear properties [1]. Durai et al. demonstrated that fiber blending ratio influenced the tensile, flexural, impact, water-absorption, and dynamic-mechanical behavior of natural-fiber composites [2]. Magibalan et al. specifically investigated sisal-

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coir epoxy hybrids and emphasized the importance of fiber orientation and hand lay-up processing [3]. Ageing and chemical-treatment effects in coir-sisal systems have also been reported [4], while comparative work on individual natural fibers has highlighted the distinct mechanical and thermal behavior of sisal and coir [5].

Other investigations have shown that moisture exposure, stacking sequence, interfacial adhesion, and fiber treatment can strongly affect hybrid-composite performance [6, 7]. Recent studies have additionally used machine-learning tools to predict mechanical properties and optimize heterogeneous natural-fiber composite systems [8, 9]. Studies on optimized sisal composites, structural applications of sisal fibers, coupling-agent modification, and filler-assisted hybridization further demonstrate the broad design space available for improving natural-fiber composites [10–13].

In hybrid composites, high-performance synthetic fibers – such as carbon fibers – provide superior mechanical strength and stiffness, while natural fibers – such as jute – contribute to reduced material cost, lower density, and improved energy absorption characteristics. The presence of natural fibers can also enhance the damping and impact behavior of the composite, making hybrid materials suitable for semi-structural and lightweight applications. The performance of hybrid composites is strongly influenced by factors such as fiber orientation, interfacial bonding, and lamination sequence [14].

Carbon–jute hybrid composites aim to combine the advantages of both materials by partially replacing carbon fibers with jute fibers in a polymer matrix. In such hybrid systems, carbon fibers provide the required strength and stiffness, while jute fibers contribute to reduced material cost, lower density, improved impact energy absorption, and enhanced environmental sustainability. This hybridization approach enables the development of composites with acceptable mechanical performance while significantly reducing overall material cost and environmental impact [15].

An experimental study is done on the fabrication and mechanical characteristics of polyester matrix laminates strengthened with jute fabric materials using vacuum infusion techniques. The hybrid samples have provided improved strength characteristics in terms of stiffness and deformation capabilities [16]. An experimental investigation is performed on the mechanical and microstructural properties of polymer laminates by using Natural jute fibers. The experimental results reveal that the natural jute samples have enhanced the mechanical properties, thereby inducing the fabrication and microstructures of sustainable engineering composite laminates [17].

An experimental analysis on the development and strength characteristics of Natural jute fiber hybrid composites. The results of this analysis have shown that the significant improvements in the strength performance of hybrid laminates [18]. The research is done on the fabrication and mechanical properties of hybrid laminates composing of jute and carbon fiber components. The results of this study have indicated that the hybrid composites have shown the increased mechanical properties for achieving environmental sustainability [19].

The superior capability of sustainable materials has induced the synthesis of Natural fiber laminates for structural and tribological uses. The fabricated samples have shown the capability of enhanced wear resistance, and less friction properties for use in tribological applications [20]. An experimental study is conducted on the development and strength characteristics of green composites. The experimental implications have shown that the selection of green composites have replaced the synthetic composites for use in bio-degradable applications [21].

This study employed bleached jute fabric and non-woven glass fabric to develop neat jute, neat glass, and hybrid composites by using different stacking sequences. However, this study suggested that jute and nonwoven glass fabric with different stacking sequences may be combined to create a reinforced hybrid composite that may have potential use in furniture, interior design, and inner sections of cars

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[22]. The experimental analysis is done on the fabrication and mechanical properties of hybrid polymer composites. The composite laminates are fabricated by hand lay-up technique. The results have indicated the natural polymer laminates have improved strength characteristics when compared to the jute fiber laminates [23]. In spite this progress, the project report identified a need for direct comparison of a sisal-dominant sisal-coir/epoxy laminate with a GFRP/epoxy comparator fabricated and tested under similar laboratory conditions. Accordingly, the present work evaluates a hybrid reinforcement containing 75% sisal fiber and 25% coconut coir fiber. The objective is to compare tensile strength, flexural strength, and impact energy and to assess whether the hybrid system warrants further development for low- to medium-load-bearing engineering applications.

MATERIALS AND METHODS

Materials

Sisal fiber was used as the primary reinforcement and coconut coir fiber as the secondary reinforcement. Epoxy resin LY556 and hardener HY951 formed the matrix system. Glass fiber was used to prepare the GFRP/epoxy comparison laminate. The present research project provides the representative material–property ranges summarized in Table 1. These values are background material specifications reported in the source project and were not independently re-measured in the present test program.

Table 1. Properties of materials.

Material	Density (g/cm³)	Tensile strength (MPa)	Young's modulus (GPa)	Elongation at break (%)
Sisal fiber	1.30–1.50	400–700	9–22	2–3
Coconut coir fiber	1.15–1.25	100–250	4–6	15–30
Epoxy resin	1.10–1.20	70–85	–	–
Glass fiber	2.50–2.60	2000–3500	70–80	2.5–4.8

Fiber Preparation and Laminate Design

Sisal and coconut coir fibers were cleaned to remove dust and surface contaminants, washed, dried to reduce moisture, and cut to the required dimensions before fabrication. The hybrid reinforcement was designed at a 75:25 sisal-to-coir proportion. The source report describes a sisal-dominant layered arrangement, with sisal positioned to provide load-bearing capability and coir incorporated to increase toughness and energy absorption. The sisal and coconut coir fibers were subjected to physical pre-treatment consisting of cleaning, water washing, controlling drying, cutting to the required dimensions, and dry storage before composite fabrication. No chemical surface treatment was applied to the fibers in the present study. The physical preparation was mainly intended to remove impurities and moisture and to improve wetting and bonding between the natural fibers and the epoxy matrix. The rationale for selecting the physical fiber-treatment method – cleaning, washing, drying, cutting, and dry storage – was mainly to improve the condition of the natural fibers beforehand lay-up without chemically modifying them. The study explains that natural fibers may contain dust, wax, moisture, and other surface contaminants, which can reduce bonding between the fibers and the epoxy matrix. Therefore, the fibers were cleaned and washed to remove impurities and then dried before fabrication. Drying was particularly important because sisal and coir are hydrophilic. Moisture can weaken fiber–epoxy interfacial bonding; reducing moisture improves resin wetting and can support better mechanical performance of the composite. Prepared fibers were stored under dry conditions prior to lay-up. The adopted pre-treatment was physical rather than chemical and consisted of cleaning, washing, controlled drying, and cutting. It was primarily intended to remove surface impurities and moisture. Consequently, no deliberate alteration of the chemical composition of the fibers was introduced. Surface morphology and chemical composition were not specifically characterized by SEM, AFM, FTIR, or related techniques in the present study; therefore, quantitative changes in surface roughness or chemical functional groups cannot be reported. Such characterization will be considered in future work.

Hand Lay-Up Fabrication

A flat mold was cleaned and coated with a release medium. Epoxy LY556 and hardener HY951 were

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measured according to the manufacturer-recommended mixing ratio and mixed to obtain a homogeneous resin system. A resin layer was applied to the mold, followed by placement of the prepared fiber layers. Resin application and fiber placement were repeated until the required laminate thickness was obtained. A hand roller was used to improve impregnation and remove entrapped air. A flat plate and external weight were then applied to consolidate the laminate. The laminate was cured at room temperature for approximately 24 h, removed from the mold, and trimmed. A GFRP/epoxy laminate was fabricated by the same general hand lay-up route for comparison.

Specimen Preparation and Mechanical Testing

The cured laminates were cut to specimen dimensions in this research work. Tensile specimens were prepared according to ASTM D3039, flexural specimens according to ASTM D790, and impact specimens according to ASTM D6110. Tensile and three-point flexural tests were conducted using a universal testing machine, while impact energy was measured using a pendulum impact testing machine. The specimen dimensions and measured properties are summarized in Table 2.

Table 2. Mechanical-test standards and specimen dimensions used in the present research.

Test	ASTM standard	Length (mm)	Width (mm)	Thickness (mm)	Measured response
Tensile	D3039	250	25	3–5	Ultimate tensile strength.
Flexural	D790	127	12.7	3–5	Flexural strength.
Impact	D6110	80	10	3–5	Absorbed impact energy.

Data Analysis

The project report states that multiple specimens were tested and average values were considered. Individual replicate data are explicitly provided for impact testing, whereas replicate-level tensile and flexural data and measures of dispersion are not included in the source. Consequently, the present manuscript reports descriptive comparisons of the available measured values and does not apply inferential statistical tests.

RESULTS

Tensile Behavior

The tensile properties of the composite laminates, including tensile strength, Young's modulus, and elongation at break, were measured using a Universal Testing Machine (UTM) in accordance with ASTM D3039. Specimens were clamped securely in the machine, and a uniaxial tensile load was applied at a constant crosshead speed until failure. The load and elongation were recorded continuously to calculate stress–strain behavior. The experiments are performed in Micro Lab, Chennai. Figure 1 shows the specimen of Sisal with Coconut Coir Fiber and Epoxy before Tensile Testing. Figure 2 shows the specimen of Sisal with Coconut Coir Fiber and Epoxy after Tensile Testing. Figure 3 shows the Load–Displacement Curve for Sisal with Coconut Coir Fiber and Epoxy After Tensile Testing.

The GFRP/epoxy specimen exhibited an ultimate tensile strength of 94 MPa, while the sisal-coir/epoxy hybrid reached 186 MPa under the reported test conditions. Thus, the measured tensile strength of the hybrid specimen was approximately 97.9% higher than that of the GFRP comparator when calculated directly from the reported values. Figure 4 presents the comparison.

Flexural Behavior

Flexural testing was conducted to determine the compressive strength and deformation characteristics of the laminates according to ASTM D790. Specimens were placed in a compression fixture of the UTM, and axial load was applied until material failure. The experiments are performed in Micro Lab, Chennai. Figure 5 shows the specimen of Sisal with Coconut Coir Fiber and Epoxy before Flexural Testing. Figure 6 shows the specimen of Sisal with Coconut Coir Fiber and Epoxy after Flexural Testing. Figure 7 shows the Load – Displacement Curve for Sisal with Coconut Coir Fiber and Epoxy After Flexural Testing.

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Figure 1. Tensile test specimen before testing.



Figure 2. Tensile test specimen after testing.

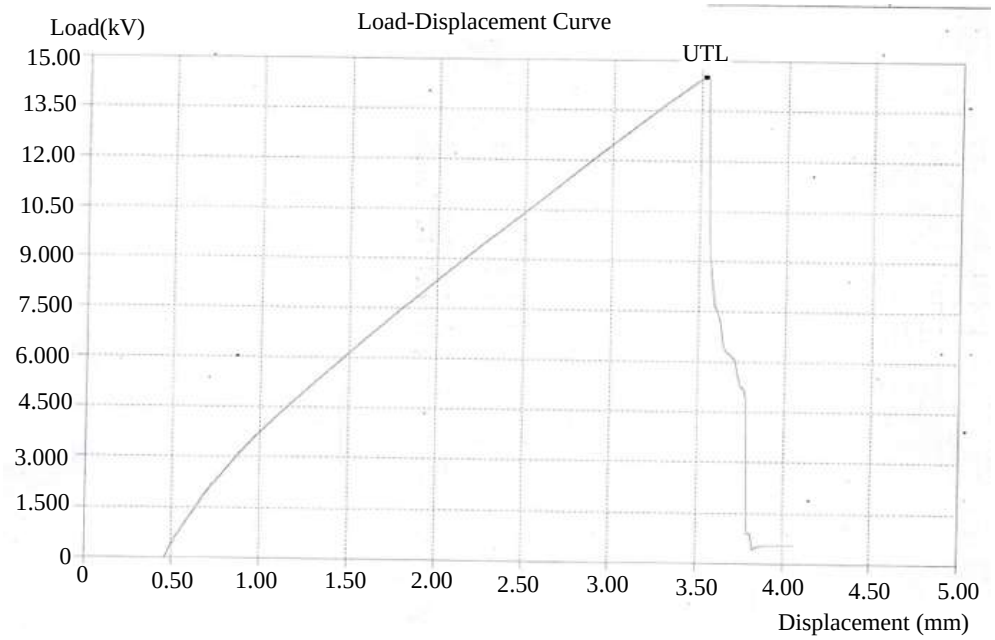


Figure 3. Load–displacement curve for tensile test.

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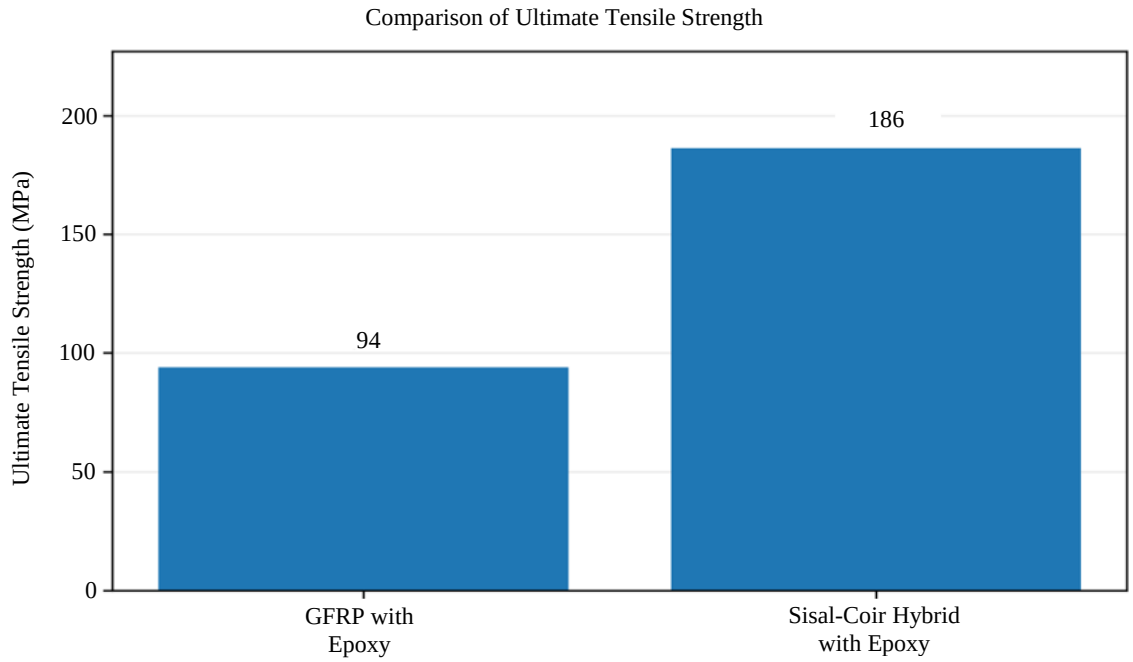


Figure 4. Comparison of ultimate tensile strength for the GFRP/epoxy and sisal-coir/epoxy hybrid specimens.

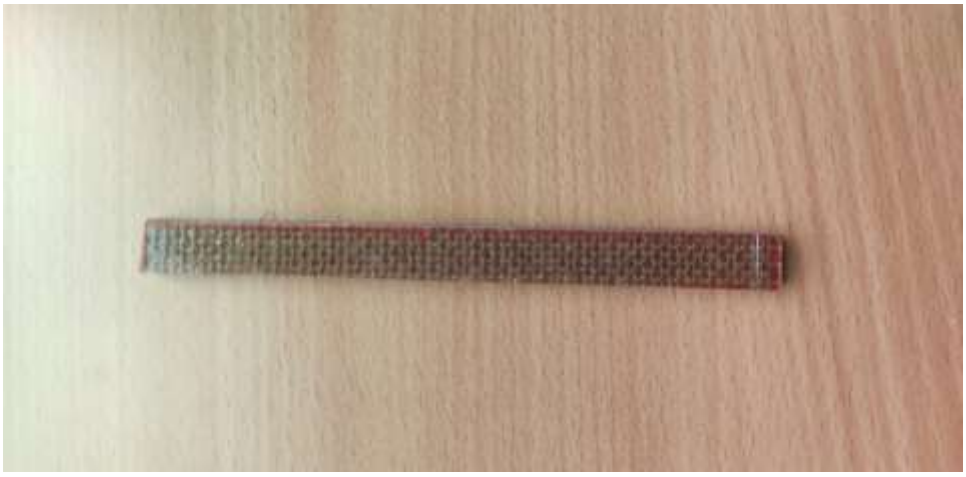


Figure 5. Flexural test specimen before testing.

The flexural strength reported for GFRP/epoxy was 132.10 MPa. The sisal-coir/epoxy hybrid exhibited a flexural strength of 313.78 MPa, corresponding to an approximately 137.5% higher measured value relative to the GFRP comparator. Figure 8 shows the reported flexural-strength comparison (Figure 8).

Impact Behavior

Impact strength was measured using a Charpy or Izod impact testing machine following ASTM D6110. The test involved striking the specimen with a pendulum hammer to determine the energy absorbed by the composite during sudden loading. Table 3 shows the impact test results for the fiber metal specimen laminates. The experiments are performed in Micro Lab, Chennai. Figure 9 shows the specimen of Sisal with Coconut Coir Fiber and Epoxy before Impact Testing. Figure 10 shows the specimen of Sisal with Coconut Coir Fiber and Epoxy after Impact Testing.

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Figure 6. Flexural test specimen after fracture.

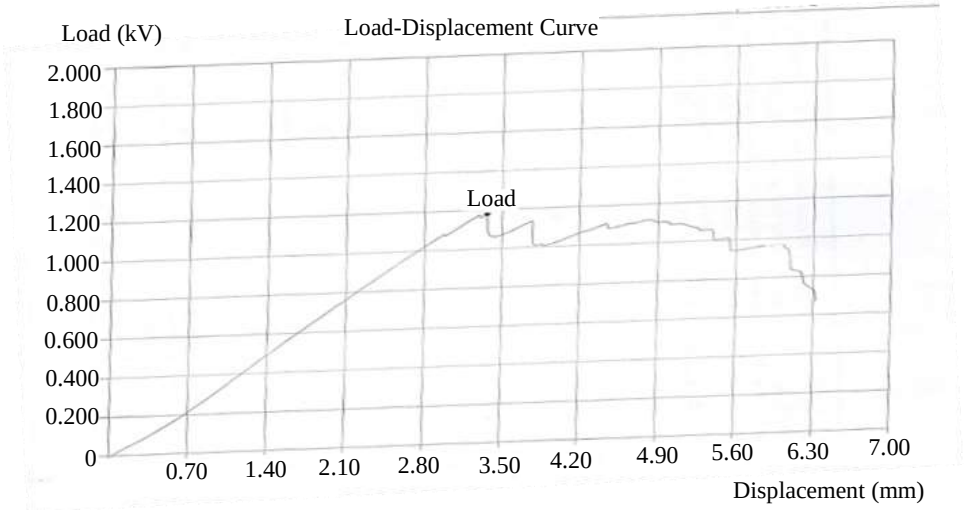


Figure 7. Load–displacement curve for flexural testing.

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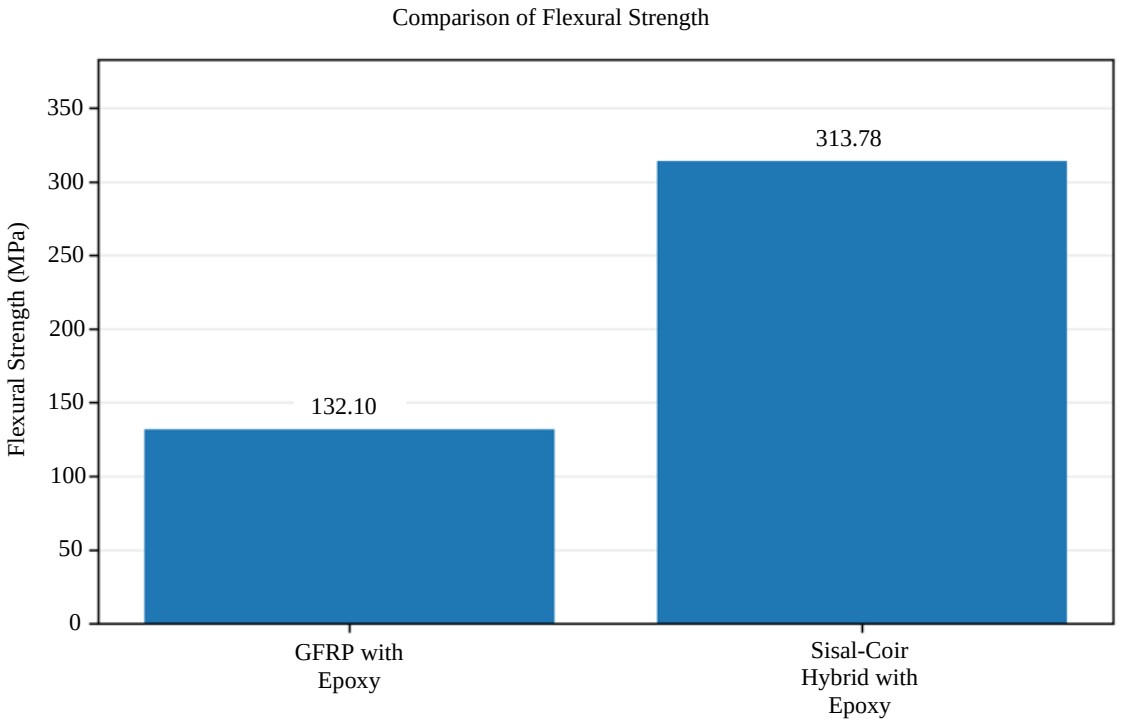


Figure 8. Comparison of flexural strength for the GFRP/epoxy and sisal-coir/epoxy hybrid specimens.

For impact testing, the GFRP/epoxy specimens absorbed 8, 8, and 8 J, giving an average of 8.00 J. The sisal-coir/epoxy specimens absorbed 10, 10, and 8 J, giving an average of 9.33 J. The hybrid, therefore, showed an approximately 16.6% higher average absorbed energy based on the reported measurements. The individual values are listed in Table 3, and the mean comparison is shown in Figure 11.

Table 3. Reported impact-energy measurements.

Composite	Specimen 1 (J)	Specimen 2 (J)	Specimen 3 (J)	Average (J)
GFRP with epoxy	8	8	8	8.00
Sisal-coir hybrid with epoxy	10	10	8	9.33



Figure 9. Impact test specimen before testing.

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Figure 10. Impact test specimen after testing.

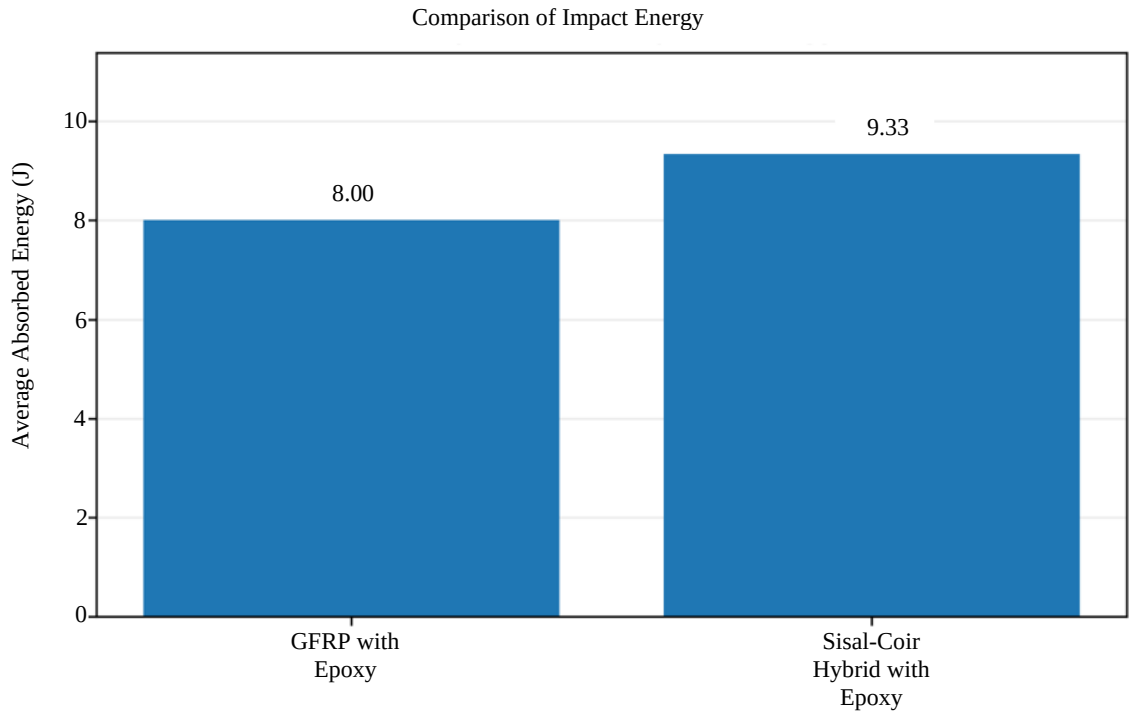


Figure 11. Comparison of average impact energy for the GFRP/epoxy and sisal-coir/epoxy hybrid specimens.

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Overall Mechanical Comparison

The overall comparison of reported mechanical properties of different samples is shown in Table 4. The representative fractured sisal-coir/epoxy tensile specimen is shown in Figure 12.

Table 4. Overall comparison of reported mechanical properties.

Property	GFRP with epoxy	Sisal-coir hybrid with epoxy	Calculated difference vs GFRP
Ultimate tensile strength (MPa)	94.00	186.00	+97.9%
Flexural strength (MPa)	132.10	313.78	+137.5%
Average impact energy (J)	8.00	9.33	+16.6%



Figure 12. Representative fractured sisal-coir/epoxy tensile specimen.

DISCUSSION

The principal finding of the project report is that the 75% sisal-25% coconut coir hybrid laminate produced higher measured tensile, flexural, and impact responses than the GFRP/epoxy comparator under the reported laboratory conditions. The source report attributes the tensile and flexural response primarily to the relatively high load-bearing contribution of sisal fibers and the impact response to the toughness and energy-absorption characteristics of coconut coir. This interpretation is consistent with the broader rationale for natural-fiber hybridization, in which complementary fiber properties are combined to reduce the limitations of a single reinforcement [1–3, 7].

The strong measured flexural response is also compatible with the project report's layered laminate concept, because bending performance depends on reinforcement placement, interfacial load transfer, and resistance to crack initiation and propagation. Prior work has shown that fiber orientation, stacking arrangement, and fiber fraction can substantially influence mechanical performance in natural-fiber composites [1, 3, 7]. The present report does not provide microscopy or quantitative void-content measurements, so mechanisms – such as improved interfacial adhesion or delayed crack propagation – should be regarded as plausible interpretations rather than directly verified microstructural observations.

The impact results provide replicate-level evidence that the hybrid laminate absorbed more energy on average than the GFRP comparator. Coir is characterized in the source report as a relatively high-elongation, high-toughness natural fiber, and the measured increase in impact energy is consistent with

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its intended role in the hybrid architecture. Studies of coir-sisal systems and other natural-fiber composites have likewise shown that treatment, ageing, moisture, and reinforcement composition affect mechanical and dynamic behavior [4–6]. These factors are important because the present project did not evaluate moisture conditioning, long-term ageing, fatigue, or thermal durability.

The measured values should be interpreted within the limitations of the available project data. The report does not provide complete replicate-level tensile or flexural results, standard deviations, confidence intervals, exact total fiber volume fraction, laminate density, or a quantified void fraction.

These omissions prevent statistical significance testing and make it difficult to generalize the observed superiority beyond the specific specimens tested. Additional controlled experiments with larger replicate sets, precise fiber/matrix volume fractions, dimensional tolerances, and uncertainty reporting are, therefore, required. Surface treatment and coupling-agent strategies may also be evaluated because improved fiber–matrix interaction has been associated with enhanced natural-fiber composite properties [12].

Future work may extend the experimental program to moisture absorption, environmental ageing, thermal characterization, fatigue, and microscopic failure analysis. Data-driven approaches have recently been used to predict and optimize mechanical behavior across heterogeneous natural-fiber composite datasets [8, 9], and could be applied once a sufficiently large experimental dataset is available. More broadly, recent work on sisal structural applications and hybrid natural-fiber composites indicates that the most credible pathway to engineering adoption is application-specific optimization rather than a universal replacement of synthetic reinforcement [10, 11, 13].

CONCLUSION

A sisal-coconut coir fiber-reinforced epoxy hybrid composite containing 75% sisal and 25% coconut coir reinforcement was fabricated by hand lay-up and compared with a GFRP/epoxy composite. Under the reported experimental conditions, the hybrid composite achieved an ultimate tensile strength of 186 MPa, a flexural strength of 313.78 MPa, and an average impact energy of 9.33 J. The corresponding GFRP/epoxy values were 94 MPa, 132.10 MPa, and 8.00 J.

The project results, therefore, show higher measured tensile, flexural, and impact performance for the hybrid specimen set. The complementary roles assigned to sisal for strength and coir for toughness provide a reasonable design basis for further development of the hybrid laminate for low- to medium-load-bearing components. However, confirmation through larger replicate populations, statistical analysis, environmental durability testing, controlled fiber-volume measurements, and microstructural characterization is necessary before broad substitution claims are made.

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