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Research Article

Experimental Study of Woven Glass, Bamboo, and Jute Fibre Reinforced in Epoxy Composites

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ABSTRACT

Industries like aerospace, automotive, marine, and transportation require materials that are lightweight yet strong, durable, and impact-resistant. To meet these demands, advanced composite materials are being developed using natural fibres such as bamboo and jute, which are eco-friendly, abundant, and cost-effective. When combined with synthetic fibres like glass, known for its heat resistance and interfacial strength, the mechanical properties of these composites improve significantly. Fabricated using the hand lay-up method with a 70% epoxy and 30% fibre ratio, these materials were tested per ASTM standards. Studies have shown that hybrid composites reinforced with bamboo, jute, and glass fibres offer enhanced tensile, flexural, hardness, and impact strength. The S1 stacking sequence performed best, with a tensile strength of 95 MPa, modulus of 1028MPa, flexural strength of 195 MPa and modulus 54 GPa, impact toughness of 12 J/mm, hardness of 87 RHN, and thermal conductivity of 0.26 W/m·K. These composites are lightweight, strong, and thermally efficient, making them ideal for rail, power, automotive, marine, and aerospace applications.

1. Introduction

In recent years, the demand for sustainable, lightweight, and high-performance materials has grown significantly, driven by environmental regulations and the need for eco-efficient technologies [1]. Natural fibres, sourced from renewable biological resources, have emerged as promising alternatives to synthetic fibres due to their biodegradability, low density, cost-effectiveness, and ease of availability [2]. Natural fibre composites (NFCs) have found increasing applications in various industrial sectors such as automotive, aerospace, marine, and construction, owing to their favourable properties, including non-abrasiveness, superior acoustic performance, and good specific strength and modulus [3, 4]. Traditionally, fibre-reinforced polymer (FRP) composites incorporate synthetic fibres like aramid, glass, and carbon, which offer

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excellent mechanical performance and are widely available [5]. These composites are commonly used due to their dimensional stability, corrosion resistance, and weight efficiency. However, synthetic fibres contribute to environmental pollution as they are non-biodegradable and energy-intensive to process. Consequently, researchers have shifted their focus towards natural fibres as sustainable reinforcement materials in polymer composites.

Among various natural fibres, bamboo has received significant attention for its remarkable mechanical properties, rapid growth rate, and widespread availability. Bamboo fibres, extracted from culms and processed through mechanical and chemical treatments, offer high tensile strength, stiffness, and thermal stability. Compared to sisal and kenaf fibres, bamboo fibre-reinforced composites demonstrate superior mechanical and thermal properties [6-8]. The hybridisation of bamboo with other fibres, such as kenaf, further enhances flexural characteristics [9]. While combining bamboo with synthetic fibres like glass leads to improvements in impact resistance and bending strength [10]. This study specifically utilises Gigantochloa scortechinii (commonly known as Buluh Semantan), a bamboo species extensively found in Southeast Asia, known for its high strength-to-weight ratio and suitability for structural applications. In the construction industry, bamboo aged between three and five years is often recommended to ensure optimal mechanical performance [11].

Jute is another natural fibre recognised for its biodegradability, recyclability, and low environmental footprint. Jute fibre composites have demonstrated favourable mechanical properties, particularly when treated with chemical agents. Benzoyl-treated jute fibre composites exhibit superior abrasive wear resistance compared to alkaline-treated counterparts [12]. Additionally, woven jute fibres provide enhanced tensile properties compared to unidirectional configurations [13]. Hybridisation with synthetic fibres such as glass and carbon significantly improves the flexural strength, modulus, and overall performance of jute-based composites [14, 15]. Jute/glass fibre hybrids, in particular, offer superior tensile, shear, and impact properties compared to non-hybrid composites [16-18].

Natural fibre-reinforced polymer composites (NFRPCs), often classified as fully or partially green composites, have demonstrated the potential to reduce product weight by 10–30%, making them attractive for manufacturers focused on eco-efficient production [19, 20]. Natural fibres are easily extractable, economically viable, and biodegradable, with their first known application dating back to the 1920s and 1930s in aviation for reducing structural weight [21, 22]. At the end of their life cycle, products made from NFRPCs can be safely disposed of through composting or incineration, minimising environmental impact [23, 24]. Scientific studies confirm that increasing fibre strength and fibre volume fraction within a composite can enhance its overall mechanical performance [25]. The typical weaving patterns used—warp (0°) and weft (90°)—aid in optimizing stress distribution [26]. Additionally, alkali treatment with 0.1% NaOH improves the interfacial bonding between natural fibres and the polymer matrix, contributing to better mechanical integrity [27, 28].

The present study focuses on the fabrication and characterization of woven hybrid epoxy composites reinforced with glass, jute, and bamboo fibres. The composites were developed using the hand lay-up technique, and their properties were evaluated according to ASTM standards. The study investigates key characteristics such as tensile strength, flexural strength, impact toughness, hardness, and thermal conductivity to assess the performance and potential applications of these hybrid composites in structural and transportation sectors [29].

2. Constituent Material

The materials used for the composite material are as follows:

2.1. Bamboo Fibre

Bamboo fibre (BF) is an eco-friendly and natural material. The bamboo plant has faster growth compared to other natural fibres; it exhibits its growth in height as shown in Figure 1. It absorbs the carbon dioxide available in the atmosphere [30]. Bamboo fibres grow to a height ranging from 10 m to 40m Here, we find a wide variety of Bamboo plants, where they vary among more than 70 species and are found worldwide in various environments [31]. Availability of the fibre is widespread in Asia and South America. It serves as the backbone of the socioeconomic status of the society. Its use in the living facility is vast. It shows a high strength-to-weight ratio [32]. Bamboo finds its inherent character as a less dense and also not so costly material. In comparison with other natural fibres, bamboo is found to be more delicate. In the extraction of bamboo, many more methods were employed, namely chemical, mechanical, and steam explosion extraction methods. China is rich in bamboo production and hence is titled "Kingdom of bamboo," where more than 400 different types of bamboo are grown [33]. Yes, China is the global leader in the bamboo industry, both in terms of the number of bamboo species and the scale of production. The country has a vast range of bamboo species, with over 500 varieties, and it holds more than half of the world's bamboo resources. By 2010, China's bamboo plantations covered 5.38 million hectares, and this area was expanding by around 100,000 hectares every year.

Bamboo is used in a variety of industries in China, including construction, furniture, textiles, paper, and even food. With its rapid growth rate and sustainable qualities, bamboo has become an essential resource for both traditional and modern industries. The Chinese government has also been actively promoting bamboo as an eco-friendly alternative to wood and plastic, encouraging the growth of this sector. The country's bamboo industry continues to innovate, exploring new uses for bamboo and expanding its reach globally, particularly in the context of sustainability and green development. The extracted raw fibre and woven form of the fibre are shown in Figure 2 and Figure 3.

Fig. 1. Bamboo tree

Fig. 2. Extracted raw bamboo fibre

Fig. 3. Woven bamboo fibre

The essence of carbohydrates in bamboo products affects their durability, which in turn affects their lifespan [34]. Bamboo fibre is already widely utilised in the production of green bio-composites, thanks to its desirable qualities such as UV protection, moisture management, antibacterial properties, durability, and non-toxic nature [35].

2.2. Jute Fiber

Jute fiber is obtained from two main plant species: Corchorus capsularis, or white jute, which is primarily grown in Asian countries, and Corchorus olitorius, known as Tossa jute, which is mainly cultivated in African countries. These plants yield a fibre consisting of approximately 65% cellulose, 12% lignin, and 13% hemicellulose [36]. Jute fibre is the second-largest producer of natural fibres worldwide, following cotton. It is widely grown, and Bangladesh, China, India, Indonesia, and Brazil are among the top producers.

These countries benefit from jute's versatility and economic importance in various industries, such as textiles, packaging, and construction materials. In summary, jute's prominence in global fibre production is underscored by its natural composition, cultivation across continents, and extensive applications in diverse sectors of the economy.

Historically, jute was primarily used for ropes, twines, sacks, and hessian fabrics, but today, bast fibres are also being utilised in the automotive industry for seat backs [37], interior door panels, trunk liners, and so on [38]. As illustrated in the Figure. 4, the jute plant can reach a height of 2.5 m with a base stem diameter of 25 mm. Jute is a soft, long natural fibre that can be spun into solid filaments. India is the leading producer of jute fibres, with 1,968,000 tons, followed by Bangladesh with 1,349,000 tons, and China with 29,628 tons [39]. Figure 5 depicts the raw jute fibre after extraction, while Figure. 6 shows the woven form of jute fibre.

Fig. 4. Jute plant

Fig. 5. Raw jute fiber

Fig. 6. Woven Jute fiber

2.3. Glass Fibre

Woven glass fibre, commonly known as fibreglass, is a composite material composed of fine glass strands woven together to create a flexible and resilient fabric [40]. Its versatility has led to widespread use across diverse industries such as construction, automotive, aerospace, and marine. With reference to Figure 8, the weaving process allows for varied patterns and densities, imparting specific properties tailored to different applications. On a weight basis, more than 99% of glass fiber, also known as synthetic vitreous fiber, used today is spun from silicate glasses [41] which are shown in Figure 7. Fibreglass is prized for several key attributes:

a) High Strength-to-Weight Ratio: It offers robust mechanical strength while remaining lightweight.

b) Corrosion Resistance: Fibreglass is resistant to corrosion, making it durable in various environmental conditions.

c) Thermal and Electrical Insulation: It provides effective thermal insulation and serves as a good electrical insulator.

d) Cost-Effectiveness: Compared to alternative materials, fibreglass is relatively inexpensive, making it economically viable for numerous projects.

In construction, fibreglass reinforces materials like insulation, panels, and roofing due to its durability and insulation properties. In automotive and aerospace applications, it is used to manufacture body panels, interiors, and structural components due to its strength and lightweight nature. Marine industries utilise fibreglass for its resistance to moisture and corrosion in boat hulls and marine structures. Despite its benefits, fibreglass production involves chemical use and energy-intensive processes, contributing to environmental challenges. The disposal of fibreglass waste also poses environmental concerns. Efforts are ongoing to develop sustainable manufacturing techniques and improve recycling methods to address these issues and enhance fibreglass's environmental footprint. Overall, fibreglass remains a versatile and valuable material in modern industry, continually evolving to meet both performance demands and environmental stewardship goals.

Fig. 7. Raw Glass Fibers

Fig. 8. Woven Glass Fiber

Table 1 depicts the Material properties of various Natural composites (i.e., Bamboo & Jute) with those of Synthetic Materials (Glass).

Table 1. Material Properties

Property	Bamboo [42]	Jute [43]	Glass Fiber [44]
Density (kg/m3)	1.2	1.3	2.50
Tensile strength (MPa)	441	370	2400
Stiffness (GPa)	11-30	13-54	70
Young's Modulus (GPa)	35.9	22.7	73
Elongation at Break (%)	1.3	1.9	2.4

2.4. Epoxy Resin

In the plastics business, epoxy resin is known as a thermosetting matrix [45]. It was first applied to structural uses, but composite materials are now using it extensively. Additionally, the paint industry employs it as a versatile coating. Epoxy resin offers the following characteristics:

1. It boasts excellent physical properties such as abrasion resistance, toughness, and flexibility.
2. It exhibits strong adhesion to various substrates.
3. Its minimal shrinkage during curing ensures precise dimensional accuracy.
4. It demonstrates high resistance to chemicals.
5. It serves effectively as an electrical insulator.
6. As a matrix, epoxy provides superior performance at elevated temperatures compared to thermoplastics.
7. It facilitates easy fabrication and is cost-effective. The properties of Epoxy resin are shown in Table 2.

Table 2. Properties of epoxy resin

Property	Epoxy [46]
Density in gm/cm^3	1.2
Tensile strength in (Mpa)	50-60
Flexural Strength (Mpa)	130-150
Viscosity at 25^{0}C (Mpa)	9000-12000

3. Fabrication Process

3.1. Fabrication of Mold

To prepare the sample, a mild steel metallic mold is shaped to a square plate of area measuring 300mm x 300mm x 3.2 mm, where the specimen is prepared in the mold to the desired dimensions, as shown in Figure 9.

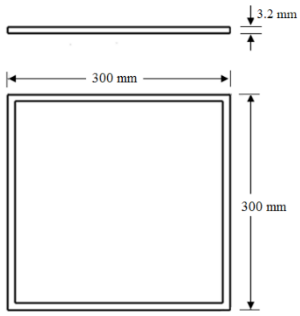


Fig. 9. Mold Box used for the preparation of the specimen

3.2. Hand Layup Technique

This is an open molding process that is simple and easy, and involves less tooling during fabrication. This process is adopted for laying the matrix and reinforcements with different orientations [47]. Figure 10 displays the process of hand lay-up for preparing the specimen.

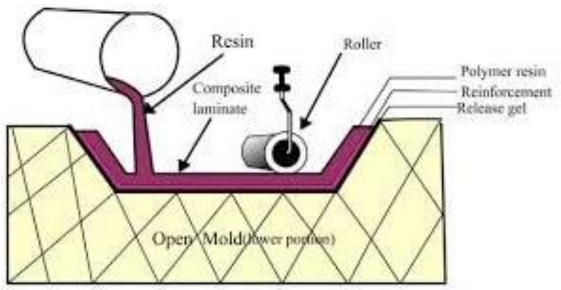


Fig. 10. Handlayup Process for specimen preparation

3.3. Rule of Mixture

The rule of mixture equation is used for the fabrication process [48, 49].

$V_c = V_f + V_m$

V_f = Volume fraction of Fibre Component

V_m = Volume of Matrix

V_c = Volume of Composite

3.4. Fabrication of Specimens

Firstly, in initiating the wet lay-up process, the mold surface is first coated with a suitable release agent, such as gel coat. This coating acts as a barrier between the mold and the composite laminate, ensuring that the fibre-reinforced materials do not adhere to the mold surface during curing. This step is essential for facilitating easy demolding and preserving the surface finish of both the mold and the final composite part.

Secondly, in the fabrication process, woven glass fibre is used as the outermost reinforcement layer, arranged in a bidirectional manner to enhance mechanical strength. The composite laminate is structured in a sandwich configuration comprising woven glass, bamboo, and jute fibres, with Lapox-12 epoxy resin serving as the matrix material. The S1 to S5 specimen series is prepared as per the lay-up sequence specified in Table 3.

The layering procedure is as follows:

1. First Layer: A single layer of woven glass fibre is placed on the mold surface in the 0° orientation (x-direction). Epoxy resin is uniformly applied over the fibre to ensure even distribution across the mold surface.
2. Second Layer: A layer of woven bamboo fiber is added in the 90° orientation (y-direction). Epoxy resin is applied thoroughly between each layer to ensure proper adhesion and resin impregnation.
3. Third Layer: A layer of jute fiber is placed in the 0° orientation (x-direction), and again coated with epoxy resin.

This sequence is repeated as necessary according to the rule of mixtures to achieve the desired thickness and mechanical properties for each specimen in the S1–S5 series, as shown in Table 3.

Table 3. The composition of composites with their respective stacking sequence is outlined as follows

Matrix %	Fibre volume %			Sample	Stacking sequence
	J	B	G		
70	10	10	10	S1	GBJBJBG
	30	0	0	S2	JJJJJ
	0	30	0	S3	BBBBBBB
	20	10	0	S4	JBJBJBJ
	10	20	0	S5	BBJBBJBB

J: Jute, B: Bamboo, G: Glass

Chemical Treatment of Natural Fibres

To improve fibre-matrix bonding, natural fibres (bamboo and jute) undergo alkali treatment using a sodium hydroxide (NaOH) solution. This treatment removes surface impurities such as lignin and wax, enhances surface roughness, and improves interfacial adhesion. It disrupts hydrogen bonding within the fibre structure, facilitating partial removal of hemicellulose and promoting cellulose exposure and depolymerisation. This process enhances the overall compatibility between the natural fibres and the epoxy matrix.

4. Characterisation

4.1. Tensile Examination

According to ASTM D3039 guidelines, tensile tests were carried out [50] in the Computerised Universal Testing Machine (UTM) with the specifications displayed in Table 4. The sample for the test was prepared according to the specifications as shown in Figure 11

Table 4. Computerised UTM Parameters

Capacity	1 Ton
Maximum Extension	1000 mm
Cross Head Speed	1 to 800 mm/min

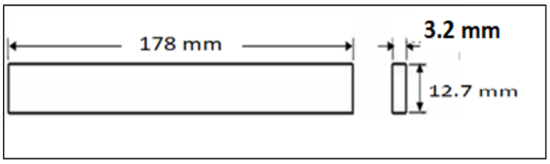


Fig. 11. Tensile Test Specimen dimensions

A computerized Universal Testing Machine (UTM) with a 100 kN capacity was used for the testing. The specimen was fixed firmly in the tensile fixture and subjected to a constant crosshead displacement rate of 5 mm/min. At room temperature (25°C), the test was conducted as displayed in Figure 12. From the curve obtained in the Stress vs Strain Plot, tensile properties of the specimen are noted, which include tensile strength, elongation at break, and Young's modulus.

Fig. 12. Computerised Universal Testing Machine for Tensile Test

4.2. Flexural Test

ASTM D790 was followed when conducting the flexural tests [51]. For conducting the Test, specimens were cut from the layup to the required dimensions with a fixed gauge length of 127 mm. The specimen for the flexural test is prepared according to the standards, as shown in Figure 13.

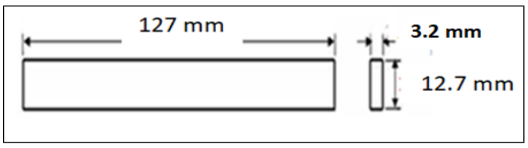


Fig. 13. Flexural test specimen dimensions

The specimens were placed in a three-point bending fixture on a computerised Universal Testing Machine (UTM), as displayed in Figure 14. Flextural test, also called the bending test, which can be checked at three noted distances

The UTM has the following specifications displayed in Table 4. And with a 100 kN capacity. A constant crosshead speed of 2 mm/min was applied during testing. Flexural properties, such as flexural strength and flexural modulus, were determined from the resulting load-displacement data, and the readings were recorded for analysis.

4.3. Impact Toughness Test

Impact damage initiation in composite materials often involves matrix cracking, fibre/matrix debonding, and delamination, particularly under low-impact energy levels. At higher impact energies, damage can progress to fibre breakage and pullout. Therefore, assessing the impact resistance of hybrid fibre-reinforced thermoplastic toughened epoxy laminates is crucial.

To assess the impact resistance of different specimens, the Charpy impact test was utilized, adhering to the ASTM D256 [52] dimensions of 64 x 12.7 x 3.2 mm. The purpose of this test was to evaluate the materials' resistance and impact toughness under controlled impact conditions.

Fig. 14. Computerized Flexural Testing Machine setup and specification of UTM

4.4. Hardness Test

A Rockwell hardness testing machine was used to conduct the hardness test in accordance with ASTM D785 [53] guidelines. A ball indenter was used to apply progressively increasing pressure to the specimens until visible deformation occurred. Five specimens were tested at different locations on each specimen, and the results were averaged to determine the overall hardness. The Rockwell hardness scale (HR) was employed to calculate the Rockwell hardness number, which quantifies the material's resistance to localized plastic deformation.

4.5. Thermal Conductivity

In compliance with ASTM E1530, thermal conductivity tests were carried out in steady-state conditions [54]. The instrument used disc-shaped specimens that were 50 mm in diameter and 10 mm thick. By dividing the constant heat flux by the temperature differential between the specimen's top and bottom surfaces, the thermal conductivity was determined. An electric heater supplied a constant heat flux, guaranteeing a consistent supply of heat for the test.

$$K = \frac{QXt}{A\,\Delta\,T} W/mK$$

where,

- Q= Heat in W, V in Volts, I in Ampere
- Q=V x I =30x0.05=1.5 watts
- A= area of specimen in mm2
  = 1.963x10-3 mm2
- t= thickness = 10mm
- ΔT = Bottom surface Temperature of specimen- top surface temperature of specimen

4.6. SEM Analysis

It is an effective instrument for research. The highly concentrated electron beam creates intricate, high-magnification images of the materials to investigate surface topography. The Hitachi SU3500 SEM analyzer is utilised in this test. It uses an objective lens with reduced aberration. It provides a higher low-kV emissions current and a better bias function [55].

5. Results and Discussions

Bamboo and jute fibres, which are primarily composed of cellulose, along with minor amounts of hemicellulose and lignin, form heterogeneous lignocellulosic structures. These fibres' abundance of hydroxyl groups makes them naturally hydrophilic. Because of this, they don't work well with hydrophobic matrices like epoxy resins. However, bamboo and jute fibres treated with alkali have a reduced number of hydroxyl groups, enhancing their compatibility with the epoxy matrix. Better mechanical properties result from this alteration, which strengthens the overall bond between the fibres and the matrix. The material is further strengthened by the addition of glass fibres to the composite samples' surface. Because of their exceptional strength and stiffness, glass fibres enhance the composite material's overall performance and structural integrity.

5.1. Tensile Test

Figure 15 depicts the variance of stress-strain curves for various stacking sequences. The samples are made of hybrid composites such as glass, bamboo, and jute fibres that have been reinforced with epoxy fibre composites. The resin is held at 70%, and the remaining reinforcements are added at 10% each to the composite material.

The tensile properties of composite material primarily depend on factors such as fibre strength, modulus, fillers, fibre length and orientation, fibre/matrix interfacial bonding, and fibre content. The tensile strength of the composite is significantly influenced by the strength and modulus of the fibres.

It is found that the stacking sequence S1 shows the highest tensile strength among all the stacking sequences. The least tensile strength was found in the S5 stacking sequence. This is because of the presence of glass fibre along with bamboo and jute.

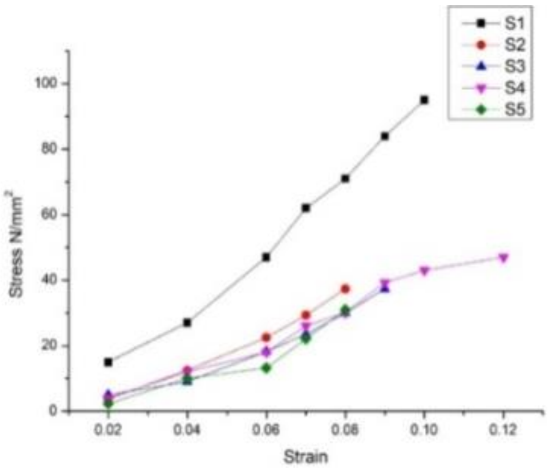


Fig. 15. Stress vs. strain curves for different hybrid fibre composites when subjected to tensile test.

The stacking sequence S1 of the composite material attained maximum tensile strength at 95 N/mm^2, S2 demonstrated a tensile strength at 37.35N/mm^2, S3 demonstrated tensile strength at 37.75N/mm^2, S4 demonstrated its maximum tensile strength at 47 N/mm^2, whereas sample S5 attained the maximum tensile strength at 30N/mm^2. The fibre-matrix interface plays a critical role in determining the mechanical properties of composite materials. At the outset, the sample S1 Hybrid polymer composites exhibit superior tensile strength and modulus when compared to pure woven jute/ bamboo composites. When S1 is compared with S5, the tensile strength is 68% greater than that of the S5 stacking sequence. Also, the moisture absorption of the composite material can be avoided or minimised by using glass fibres, which are stacked at the outermost layers. When the hybrid natural composites made up of bamboo and jute fibres, i.e., S3, S4, and S5 compared with each other, it was found that as the percentage of jute fibre increased, the tensile strength of the composite material increased. The sample S2, i.e., pure bamboo composite, shows the least tensile strength. This is primarily due to the highest percentage of cellulose present in bamboo fibre.

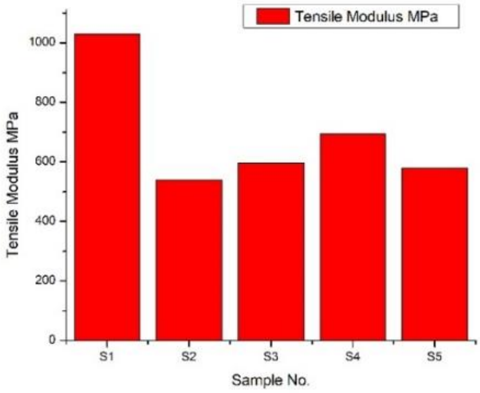


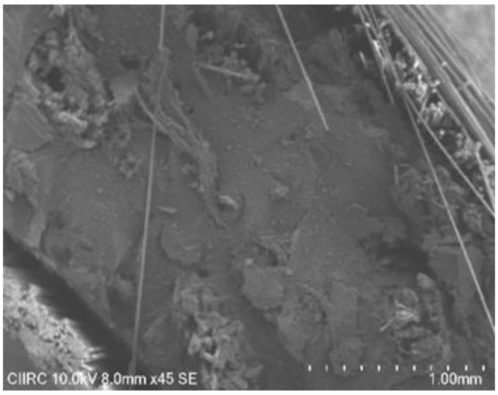
Fig. 16. Variation of tensile modulus of specimens concerning stacking sequence

Figure 16 shows the tensile modulus of specimens concerning the stacking sequence. A significant enhancement in tensile modulus is seen in specimen S1, which combines glass, jute, and bamboo fibres, compared to specimens S2, S3, S4, and S5 containing pure bamboo, jute, and hybrid composites, respectively. Specimen S1 demonstrates the highest tensile modulus of 1028 MPa among all. The presence of 10% of each fibre in the hybrid composites resulted in attaining the highest tensile modulus.

5.2. SEM Analysis of Tensile Test Specimens

A comprehensive investigation of morphological behaviour on glass, bamboo, and jute reinforced with epoxy composite enhances the mechanical properties that are competitive for structural applications [56]. The SEM analysis of specimen S1 reveals heterogeneous fracture behaviour in the hybrid composite, with failure mechanisms largely governed by the type and distribution of fibres. The quality of interfacial bonding between the fibres and Specimen S1's fracture morphology indicates adequate bonding between the fibre bundles and the matrix.

Figures 17 to 20 reveals the various specimens' SEM morphology. Scanning Electron Microscopy (SEM) is an essential instrument for analysing hybrid composites. SEM images show a good bonding strength between the fibres of the S1 sample. which is likely due to the alternative arrangements or positioning of the glass, jute, and bamboo fibres. In tensile strength, S1 composites have been indicated to be optimised at particular ratios exhibiting the most efficient design. Furthermore, the employment of a mixture of glass, bamboo, and jute fibres with polymer composites showed superior strength-to-weight ratios. The glass fibre has good adhesion with the natural fibre composites. As the glass fibres are set at the outermost layers, they can exhibit more loading conditions and safeguard the composite material from moisture absorption. Overall, these observations underscore the significance of fibre type, stacking sequence, and surface treatment in determining the mechanical behaviour of hybrid composites. The outermost woven glass material exhibits a brittle nature but also demonstrates good mechanical properties, making the specimen suitable for the needs of the present research.



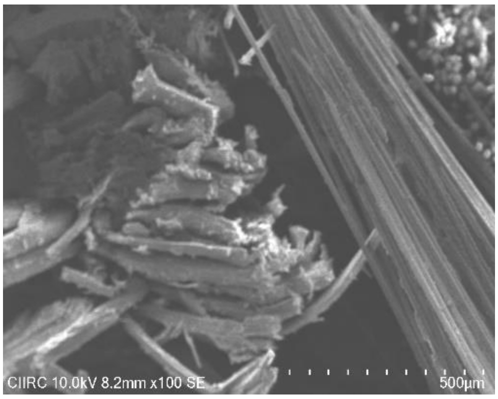


Fig. 17. S1-10 % Glass, 10% Jute, and 10% Bamboo stacking sequence

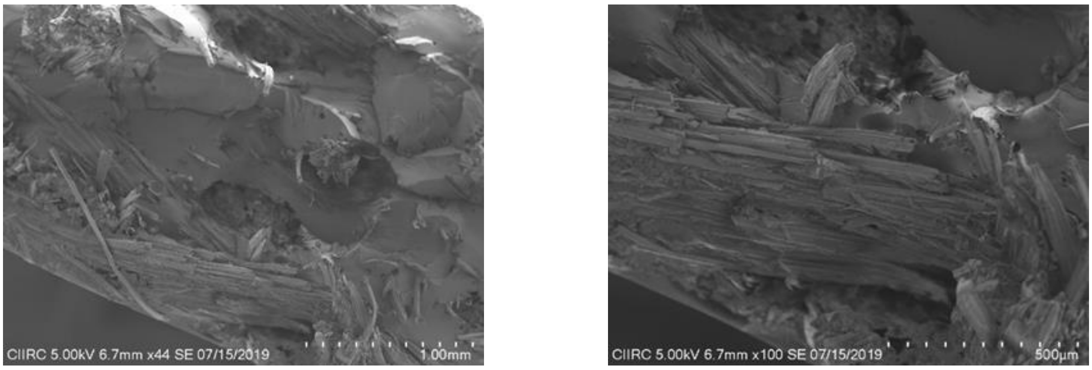


Fig. 18. S2-30% Jute Hybrid stacking sequence

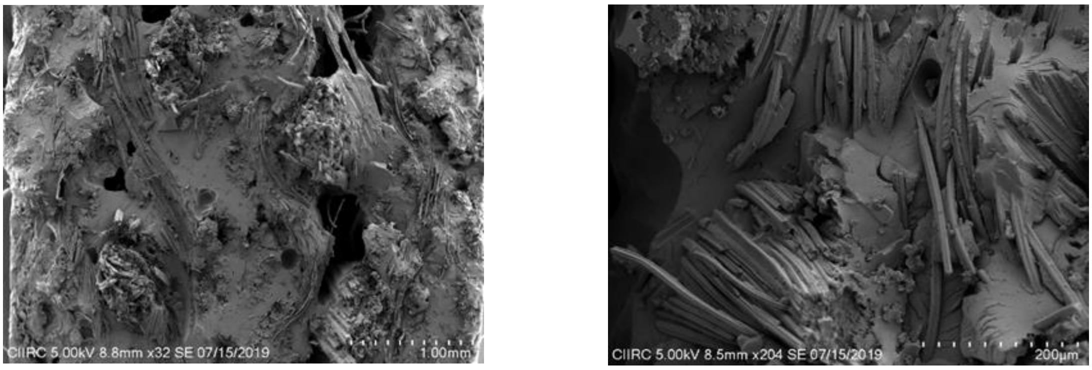


Fig. 19. S4- 20% Bamboo & 10% Jute Hybrid stacking sequence

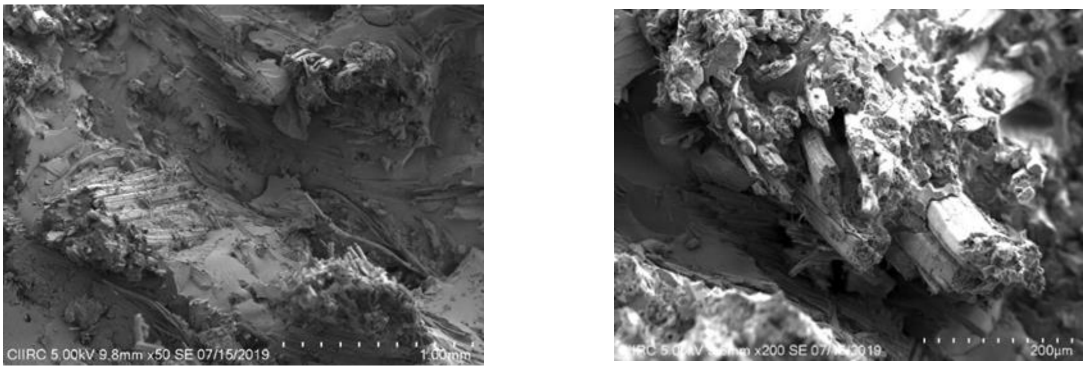


Fig. 20. S5-10% Bamboo & 20% Jute Hybrid stacking sequence

5.3. Flexural Test

Flexural testing is essential for assessing composite materials' durability and structural performance under bending loads. The test helps in knowing the valuable insights into the specimen's point of failure, maximum stress location, and stress induction, which are crucial for applications subjected to compressive forces. Additionally, bending tests enable the evaluation of parameters such as vibration response, maximum displacement, load capacity, and energy absorption capacity, thereby facilitating the development of testing tools and a deeper understanding of composite behaviour.

In a three-point bending test conducted using a Universal Testing Machine (UTM), the flexural properties of five different hybrid composites were determined. Each composite type was prepared with five specimens, labelled S1 through S5.

With reference to Figure 21, the results indicate that type S1 exhibited the highest flexural strength at 195.55 MPa before failure occurred. This demonstrates the significant improvement in bending deformation and stress resistance achieved by incorporating glass fibres into the composite, highlighting their superior strength and flexibility compared to jute fibre reinforcement.

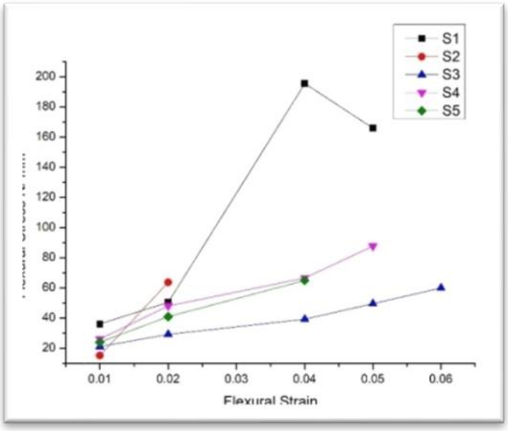


Fig. 21. Stress vs. strain curves for different hybrid fibre composites when subjected to flexural test

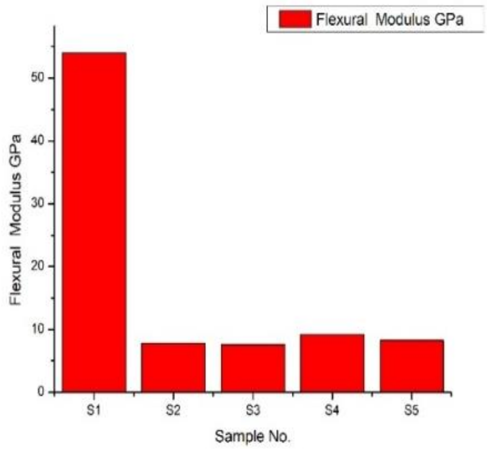


Fig. 22. Variation of flexural modulus of specimens concerning stacking sequence

Conversely, S4 reported a flexural strength of 87.74 MPa, while Type S5 exhibited a flexural strength of 65.03 MPa. The stacking sequence S2 showed a flexural strength of 63.79 MPa, and sequence S3 demonstrated a flexural strength of 59.96 MPa.These findings underscore the substantial enhancement in flexural properties achieved by incorporating glass fibres into the composite structure. This reveals that the bonding between the hybrid fibre, i.e., glass, jute, and bamboo fibres, with epoxy resin composites is adequate and yields good mechanical properties. The outer layers of glass fibre also support the composite material against moisture absorption of the composite material.

The S1 stacking sequence also shows the ductile behaviour of the material. This means that the material behaves like an elastic material for flexural loads. This property of the material may be helpful in structural applications, as well as in automobile and aerospace applications.

The variation in the flexural modulus of various specimens concerning the stacking sequence is illustrated in Figure 22. A drastic increase in the flexural modulus is observed in specimen S1, which is composed of a combination of woven glass fibre, bamboo, and jute fibres. This is in comparison to the individual bamboo, jute, and hybrid combinations of bamboo and jute fibres. Specimen S1 demonstrates the highest flexural modulus of 54 GPa, which is unmatched by the other hybrid materials. This can be attributed to the presence of glass fibre in the outer core regions of the specimen, making it more resistant to bending or deformation under load compared to the natural hybrid materials.

5.3.1. SEM Analysis of Flexural Test Specimens

SEM images reveal strong interfacial bonding between the fibres and the polymer matrix. Among all tested specimens, Specimen S1 exhibits the most distinct surface morphology, shown in Figure 23, indicating well-bonded fibre bundles and minimal interfacial defects.

The failure mechanisms in these composites are predominantly influenced by the type and distribution of fibres.

In Specimen S1, the optimized stacking sequence alternating layers of glass, jute, and bamboo fibres contributes to enhanced mechanical integrity. This arrangement ensures improved load transfer and flexural strength. Notably, the outermost layers, composed of woven glass fibre, provide significant benefits: they not only enhance mechanical performance but also protect the composite from moisture ingress due to their brittle yet robust nature. The integration of glass, bamboo, and jute fibres results in a hybrid composite with a high strength-to-weight ratio. Glass fibres, in particular, demonstrate excellent adhesion with natural fibres, and their placement on the outer layers reduces the risk of delamination under flexural loads. SEM images of Specimen S1 show minimal voids and fibre pull-out, further confirming the superior bonding and structural performance. Overall, the findings highlight the importance of fibre type, stacking sequence, and fibre-matrix interface in determining the mechanical behaviour of hybrid composites. Specimen S1 demonstrates the highest flexural strength and a balanced performance, making it the most promising candidate among all tested configurations.

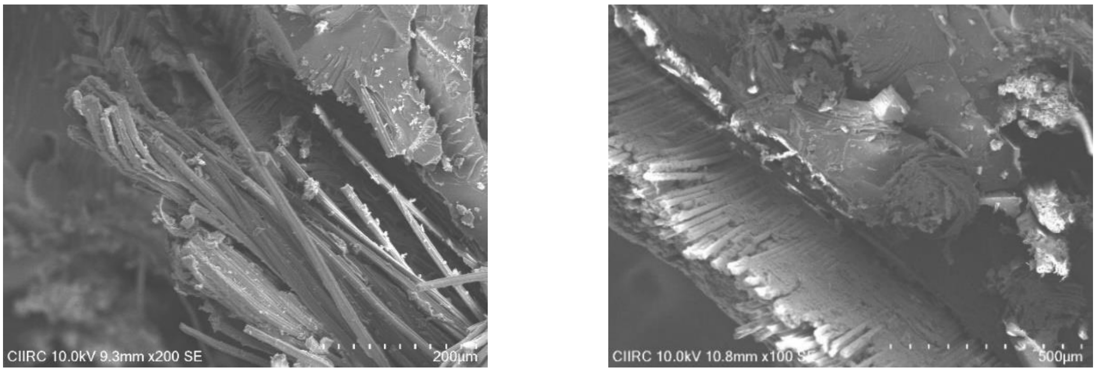


Fig. 23. S1-10 % Glass, 10% Jute, and 10% Bamboo stacking sequence

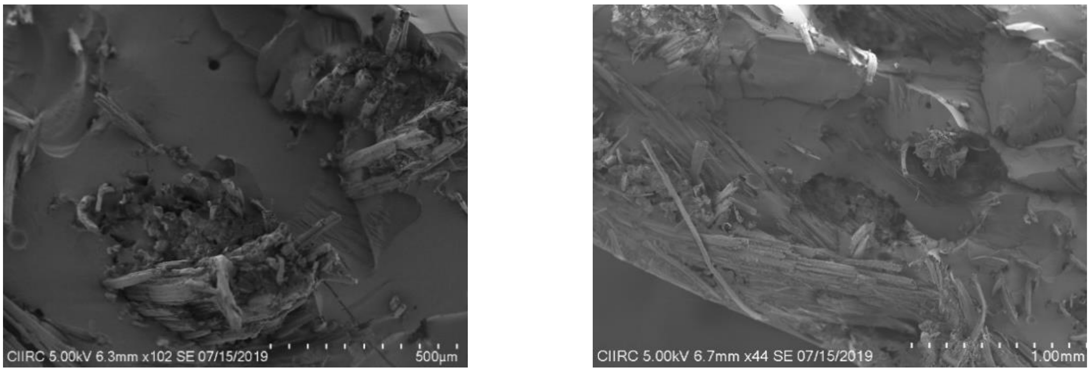


Fig. 24. S2-30% Jute Hybrid stacking sequence

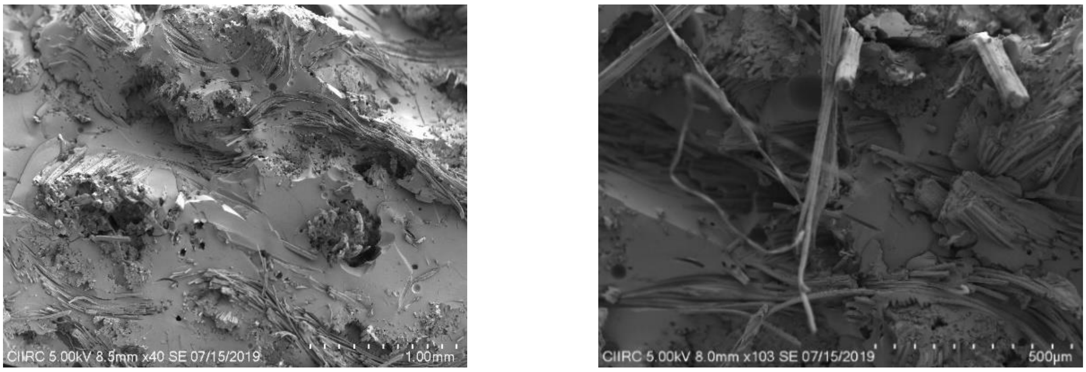


Fig. 25. S4-20% Bamboo & 10% Jute Hybrid stacking sequence

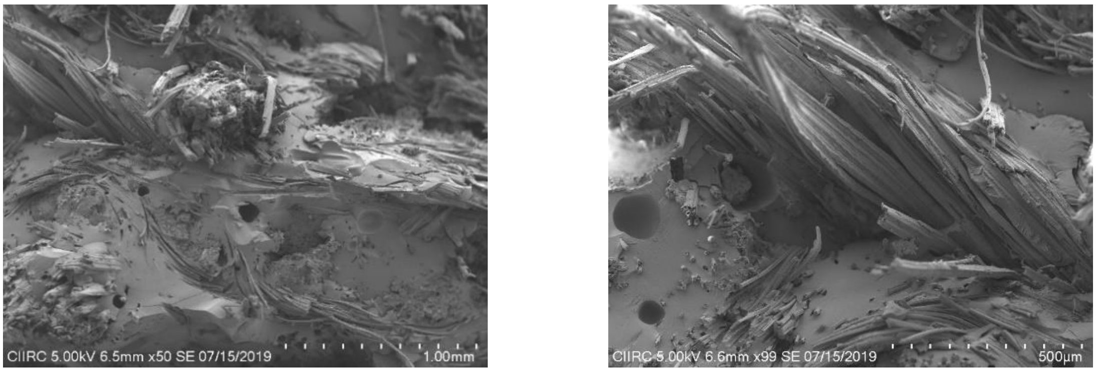


Fig. 26. S5-10% Bamboo & 20% Jute Hybrid stacking sequence

5.4. Impact Test

The impact test results for a range of composites with varying percentages of reinforcement weight are shown in Figure 27. On observing the data keenly, hybrid composites have a higher impact strength than composites made of pure jute, glass, and bamboo fibres.

Specifically, the hybrid combination of glass, jute, and bamboo fibres demonstrates the best overall performance. Specimen S1 achieves a total impact strength of 12 J/mm, highlighting its superior ability to absorb impact energy compared to the other materials tested.

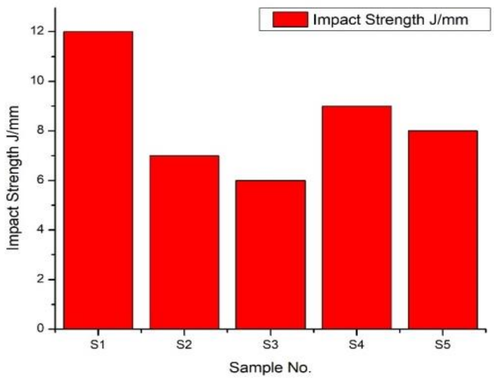


Fig. 27. Impact energy of different stacking sequences

5.5. Hardness Test

The hardness test results for different stacking sequences are shown in Figure 28. According to the data, the hybrid stacking sequence S1 is harder than the composites made of pure jute and bamboo fibres. The S1 composite exhibits the highest hardness of 87 RHN of all the sequences tested. The composition of glass fibre along with bamboo and jute provides superior hardness, as it greatly increases the material's resistance to surface deformation and indentation.

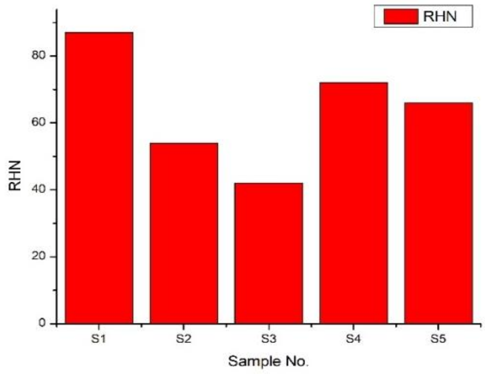


Fig. 28. Hardness number of different stacking sequences.

5.6. Thermal Conductivity

The findings of the thermal conductivity tests performed on a range of composites with varying percentages of reinforcement are shown in Figure 29. The data reveal that the hybrid composites exhibit the highest thermal conductivity, outperforming the pure glass, jute, and bamboo fibre composites. Specifically, hybrid composite S1 demonstrates the best overall thermal conductivity, with a recorded value of 0.26 W/mK. This highlights the material's superior efficiency in heat transfer compared to the other composites tested.

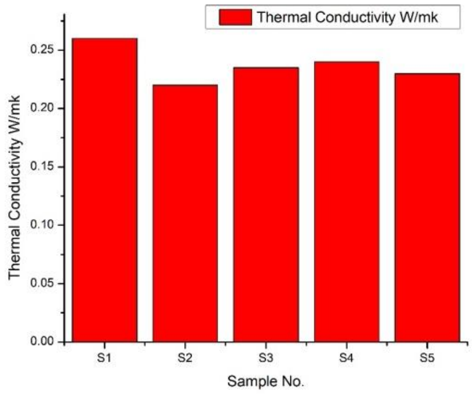


Fig. 29. Thermal conductivity of different stacking sequences

6. Conclusions

1. When compared to the S2, S3, S4, and S5 laminates, the composite with the stacking sequence S1 shows the highest tensile strength of 95N/mm^{2,} which is comparable with that of the rest of the hybrid composites.
2. The S1 sample exhibits a maximum modulus of elasticity of 1028 MPa, where the rest of the samples fall below 800 MPa.
3. Compared to specimens with stacking sequences S2, S3, S4, and S5, the specimen with the S1 sequence has a greater flexural strength of 195.55 Mpa.
4. The S1 laminate had the highest flexural modulus, where it shows outstanding performance at 54 GPa, incomparable with the rest of the samples
5. Composite materials' capacity to absorb energy is greatly improved by hybrid laminate designs. By exhibiting superior impact load absorption and successfully postponing crack initiation and propagation, these hybrids perform better than individual fibres.
6. The Hardness of the Specimen S1, indented at 87RHN, and showing its superior strength of the material compared to other samples prepared.
7. The thermal conductivity of the S1 Sample recorded at 0.26 W/mK and found to be heat transfer efficient compared to other samples.

8. Future materials engineering could benefit greatly from the development and use of advanced hybrid fibre composites, which could lead to the production of new high-performance materials.

Nomenclature

NFRPC	Natural Fibre Reinforced Polymer Composite
NaOH	Sodium Hydroxide
GF	Glass Fiber
BF	Bamboo Fiber
JF	Jute Fiber
UTM	Universal Testing Machine
ASTM	American Society for Testing and Materials
NFC	Natural Fibre Composites

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Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this article.

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