IJCRT.ORG ISSN : 2320-2882

INTERNATIONAL JOURNAL OF CREATIVE RESEARCH THOUGHTS (IJCRT)

An International Open Access, Peer-reviewed, Refereed Journal

Experimental Analysis And Optimization Of Composite Structure For Roofing Panels

Binapalepu Prasanna Kumar[1], M. Bala Krishna[2]

Department of Mechanical Engineering, Godavari Institute of Engineering & Technology (A)

Rajahmundry, A.P, India.

Abstract - The demand for sustainable and high-performance roofing materials has intensified due to the environmental and mechanical limitations of asbestos, cement sheets and galvanized iron (GI). This study investigates a hybrid composite reinforced with basalt, hemp and banana fibres using LY556 epoxy, fabricated through the hand lay-up method in 3 mm and 5 mm thicknesses. Mechanical and physical evaluations, including tensile strength, flexural strength, hardness and water absorption were conducted according to ASTM standards. A material-properties-driven Multi-Criteria Decision-Making (MCDM) optimization methodology was applied to identify the most suitable stacking sequence by considering tensile strength, flexural strength, water absorption, density, cost, availability and sustainability. This approach identified Basalt-Hemp-Banana for the 3 mm laminate and a symmetric Basalt-Hemp-Banana-Hemp-Basalt configuration for the 5 mm laminate.

The 5 mm optimized laminate demonstrated improved performance compared to asbestos and cement roofing materials, achieving a tensile strength of 88 MPa and a flexural strength of 158 MPa, exceeding the values reported for asbestos and cement roofing materials. The laminate exhibited a Shore D hardness of 70 and a low water absorption of 0.73%, indicating strong durability and suitability for humid climates. The results confirm that the optimized hybrid composite is a viable, lightweight and eco-friendly alternative to selected conventional roofing solutions.

Keywords - Basalt, Banana, Hemp, Epoxy resin LY556, Roofing panels, Hybrid composite.

1. Introduction

The demand for sustainable, lightweight and durable roofing materials has increased due to the mechanical limitations and environmental concerns associated with asbestos, cement sheets and galvanized iron (GI). Natural fibre–reinforced polymer composites are attractive due to their low density and renewable nature; however, banana and hemp fibres often exhibit limited strength and higher moisture uptake, which can restrict their long-term performance in outdoor environments. Hybridization with high-performance fibres provides an effective solution to these limitations. Basalt fibre offers high tensile strength, thermal stability and weathering resistance, making it suitable for enhancing the structural performance of hybrid laminates. The stacking sequence of such laminates significantly influences flexural stiffness, durability and moisture resistance. In this study, a hybrid composite comprising basalt, hemp and banana fibres with LY556 epoxy was fabricated using the hand lay-up method in 3 mm and 5 mm thicknesses. Mechanical and physical properties were evaluated according to ASTM standards. A material-properties-based Multi-Criteria Decision-Making (MCDM) approach was employed to optimize the stacking sequence, resulting in Basalt–Hemp–Banana and Basalt–Hemp–Banana–Hemp–Basalt configurations. The study focuses on experimentally evaluating the mechanical and moisture-related behaviour of the developed hybrid laminate for roofing use, indicating the composite's suitability as an eco-friendly roofing material.

2. Literature Review

Natural fibre-reinforced polymer composites (NFRPCs) have gained increasing attention as lightweight and sustainable alternatives to traditional construction materials [1], [2]. Their low density, biodegradability and favourable specific stiffness make them suitable for non-load-bearing and semi-structural applications. However, limitations such as moisture absorption and lower tensile strength compared to synthetic fibres restrict their performance in outdoor environments [3], [4].

Banana fibre offers moderate tensile properties and good energy absorption but suffers from high hydrophilicity, affecting its durability under humid conditions [5]-[8]. Hemp fibre provides higher stiffness and improved interfacial bonding, especially when subjected to chemical treatments such as alkali or silane modification, which reduce water uptake and enhance mechanical performance [9]-[11].

Basalt fibre has emerged as a high-performance reinforcement with superior tensile strength, thermal stability and chemical resistance compared to many natural and synthetic fibres [12], [13]. Basalt-natural fibre hybrids show significantly improved tensile, flexural and impact behaviour, making them suitable for applications requiring high surface durability and bending resistance [14]-[17].

Moisture uptake is a major concern in natural fibre composites because the hydroxyl groups present in lignocellulosic fibres promote swelling, weaken fibre–matrix bonding, and contribute to long-term material degradation [18], [19]. Hybridization with low-absorption fibres such as basalt and positioning natural fibres away from exposed surfaces have been shown to effectively reduce water uptake [20].

Stacking sequence plays a major role in determining laminate mechanics. Placing stiff fibres such as basalt in the outer layers enhances flexural strength and hardness, while natural fibres in the core reduce weight and cost [21], [22]. Symmetric stacking has been found to improve dimensional stability and impact tolerance in hybrid laminates. Hand lay-up continues to be an accessible and widely used fabrication process for hybrid natural fibre composites in prototyping and low-cost manufacturing [23]. Optimization methods such as Multi-Criteria Decision-Making (MCDM) provide an effective framework for selecting fibres and determining stacking sequences when multiple mechanical and environmental factors must be considered [24].

2.1 Research Gap and Problem Statement

Conventional roofing materials such as asbestos, cement sheets and galvanized iron (GI) suffer from health risks, inadequate mechanical performance and durability issues, while also raising sustainability concerns. Although hybrid composites combining natural and synthetic fibres have shown promise, limited research has focused on tri-hybrid systems specifically optimized for roofing applications. In particular, studies on basalt-hemp-banana fibre composites and their direct comparison with traditional roofing materials are scarce. This study addresses this gap by developing and evaluating a Basalt-Hemp-Banana epoxy composite for roofing applications, with mechanical and moisture performance compared against asbestos, cement and GI sheets.

2.2 Objectives of the Study

The objective of this study is to develop a Basalt–Hemp–Banana hybrid composite for roofing applications. The specific objectives are to: Evaluate the tensile strength, flexural strength, hardness and water absorption of the hybrid composite. Compare its performance with conventional roofing materials such as galvanized iron (GI), asbestos sheets and cement boards. Assess its suitability for roofing applications in terms of durability, sustainability and cost-effectiveness.

2.3 Novelty and Comparison with Existing Research

This study presents a novel tri-hybrid composite combining natural fibres (banana and hemp) with synthetic basalt fibre for roofing applications. While prior research has largely focused on single-fibre or dual-fibre composites, limited studies have addressed hybrid systems that effectively balance mechanical performance with sustainability. Hemp and banana fibres offer environmental benefits and low density but are constrained by moderate strength, whereas basalt fibre provides high strength and durability. The present work addresses this gap by developing an optimized Basalt–Hemp–Banana epoxy laminate with enhanced mechanical performance and reduced water absorption. The study further contributes by systematically comparing the developed composite with conventional roofing materials such as asbestos, cement and GI, demonstrating its potential for practical and sustainable roofing applications.

3. Materials and Methods

This section describes the materials used in the fabrication of the Basalt-Hemp-Banana hybrid composite and the procedures followed for laminate preparation, specimen manufacturing and mechanical testing. All steps were carried out to ensure consistency and reliability in evaluating the composite's suitability for roofing applications.

3.1 Materials

3.1.1 Reinforcement Fibres

Three different fibre reinforcements were selected. Banana fibre is a lightweight lignocellulosic material offering moderate tensile strength and good flexibility. Its low density and biodegradability contribute to the composite's sustainability and reduced weight. Hemp fibre is chosen for its comparatively higher stiffness and better fibre-matrix adhesion among natural fibres. Hemp fibre enhances structural stability while maintaining environmental benefits. Basalt Fibre is a mineral-based fibre with superior tensile strength, high thermal resistance and excellent durability. Basalt was incorporated primarily in the outer layers to improve flexural performance and environmental resistance.

Fig. 1 Banana Fabric

Fig. 2 Hemp Fabric

Fig. 3 Basalt Fabric

Table-1. Dimensions of Fabrics

S. No.	Fabric Name	Length (mm)	Width (mm)	Thickness (approx.)
1.	Hemp	1000	1000	0.3
2.	Banana	1000	1000	0.3
3.	Basalt	1000	1000	0.3

3.1.2 Matrix Material

The matrix material was an epoxy resin comprising Araldite LY556 and Aradur HY951. This combination was selected due to its high mechanical properties, good adhesion with the fibers and resistance against environmental decay. This resin is the binding agent that keeps these fibers bonded together and helps to transfer loads from one fiber to another within a composite. Araldite LY556 resin and Aradur HY951 hardener were mixed at a 10:1 weight ratio as per manufacturer's TDS. Figure 4 shows Epoxy resin used.

Fig. 4 Epoxy Resin

3.1.3 Fabrication Method: Hand Layup Technique

The composite laminates were produced using the hand lay-up process, a straightforward and widely practiced technique for polymer composites. The mould was first treated with a release agent, after which the reinforcement layers were arranged in the required sequence. Each layer was impregnated with the resin-hardener mixture and compacted with a roller to remove trapped air and ensure uniform wetting. The laminates were then allowed to cure at room temperature for 24 hours. This method is economical, easy to apply, and effective for fabricating flat composite panels. Figure 5 shows hand layup technique.

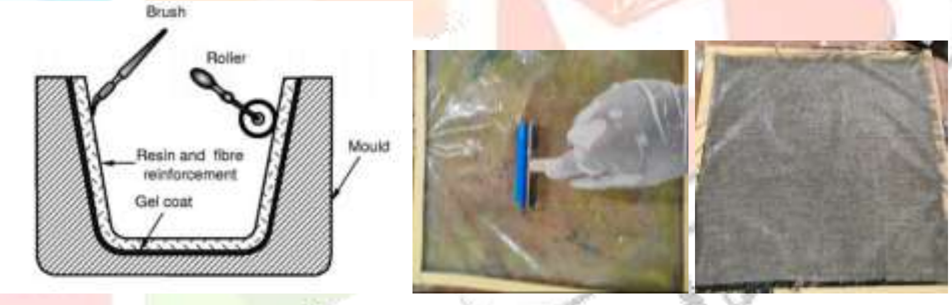


Fig. 5 Hand-Layup Process

3.2 Optimization Methodology

A weighted sum model (WSM)-based Multi-Criteria Decision-Making (MCDM) approach was employed for laminate optimization.

3.2.1 Optimization Philosophy

The purpose of the material-properties-driven MCDM method was to justify the stacking sequence selection based on reported material characteristics and roofing performance requirements. Roofing materials must withstand tensile loads, bending stresses, moisture exposure and long-term weathering. Therefore, each fibre was evaluated according to these functional demands.

The optimization framework considered that:

- Stiffer fibres provide better surface strength when placed at outer layers.
- Natural fibres perform better when protected within the core.
- Symmetry improves laminate stability and reduces warpage.

3.2.2 Selection of Criteria

Each criterion was assigned a weight based on its importance in roofing applications. Six key criteria were used to evaluate each fibre:

- Tensile Strength - essential for resisting wind uplift and handling loads.
- Flexural Strength/Stiffness - important for preventing sagging under bending.
- Water Absorption Resistance - critical for outdoor and humid environments.
- Density (Lightweighting) - lowers dead load on roofing structures.
- Cost and Availability - supports practical and economic feasibility.
- Environmental Sustainability - aligns with green material requirements.

3.2.3 Weight Assignment and Scoring

Weights were assigned between 0 and 1 such that the total weight equaled 1.
Each fibre (Banana, Hemp, Basalt) was scored on a scale of 1 to 5, where:

- 5 = Excellent performance
- 1 = Poor performance

Weighted scores were calculated using:
Weighted Score=Criterion Weight x Fibre Score
The total score for each fibre was obtained by summing all weighted values.

Table-2. Material Properties

S.No	**Property**	**Hemp Fibre**	**Banana Fibre**	**Basalt Fibre**
1	Density (kg/m³)	1450	1350	2650
2	Young's Modulus, E (GPa)	32	25	90
3	Poisson's Ratio (μ)	0.30	0.32	0.25
4	Tensile Strength (MPa)	700	450	3000
5	Flexural Modulus (GPa)	22	18	85
6	Thermal Conductivity (W/m-K)	0.25	0.30	0.22
7	Water Absorption Tendency	Moderate	High	Low
8	Sustainability Level	High	Very High	Moderate
9	Cost & Availability	Low / High	Low / High	Moderate / Medium

3.2.4 Decision Matrix

The results of the MCDM evaluation are shown below.

Table-3. Decision Matrix

Criterion	Weight	Banana	Hemp	Basalt	Weighted Banana	Weighted Hemp	Weighted Basalt
Tensile Strength	0.25	3	4	5	0.75	1.00	1.25
Flexural Strength	0.20	3	3	5	0.60	0.60	1.00
Water Absorption	0.15	2	3	4	0.30	0.45	0.60
Density	0.10	4	3	2	0.40	0.30	0.20
Cost & Availability	0.15	4	4	3	0.60	0.60	0.45
Sustainability	0.15	5	5	3	0.75	0.75	0.45
Total Score	1	-	-	-	3.40	3.70	3.95

Basalt showed the highest overall weighted score, followed by Hemp and Banana.

3.2.5 Optimization Outcome

From the decision matrix, the following conclusions were derived:

Basalt, with the highest strength and best moisture resistance, was most suitable for the outer layers. Hemp, which balances stiffness and sustainability, was placed in intermediate positions. Banana, being lightweight but less moisture-resistant, was positioned in the core, where it is protected from environmental exposure.

Thus, the optimized stacking sequences were determined as:

Optimized Stacking Sequences**:** 3 mm laminate- Basalt / Hemp / Banana & 5 mm laminate (symmetric for better stability): Basalt / Hemp / Banana / Hemp / Basalt.

3.2.6 Significance of the Optimization Approach

The proposed MCDM-based optimization method:

The proposed approach ensured a scientifically justified stacking sequence without relying on computational simulations, with the selected weights based on roofing functional requirements reported in previous composite roofing studies. The developed laminates exhibited improved tensile and flexural strength based on experimental test results, reduced water absorption, and enhanced durability. The methodology enabled effective integration of natural and synthetic fibres while supporting sustainability objectives. Furthermore, the study demonstrates a practical and replicable framework that can be adopted for future hybrid composite material development.

3.3 Fabrication of Hybrid Composite Laminates

Hybrid composite (3 mm & 5 mm) laminates were prepared using the hand lay-up approach, valued in composite technology for its simplicity, affordability and time-saving nature.

3.3.1 Stacking Sequence Design

The stacking sequence was determined using a material-properties-based MCDM optimization method, evaluating tensile strength, stiffness, moisture resistance density, cost and sustainability. The optimized sequences were:

- 3 mm laminate: Basalt / Hemp / Banana
- 5 mm laminate: Basalt / Hemp / Banana / Hemp / Basalt (symmetric)

This arrangement ensures high bending stiffness and low water absorption, with natural fibres positioned away from the exposed surfaces.

3.3.2 Lay-Up Procedure

The mould surface was cleaned and coated with a wax release agent. Basalt, Hemp and Banana Fabrics were cut to the required dimensions corresponding to the laminate panel size (400 mm x 400 mm). Epoxy LY556 and hardener HY951 were mixed in a 10:1 ratio and stirred until a homogeneous mixture was obtained. Layers were placed on the mould surface and impregnated with epoxy resin for 3 mm (Basalt / Hemp / Banana) & 5 mm (Basalt / Hemp / Banana / Hemp / Basalt (symmetric)). Air bubbles were removed using a hand roller to achieve uniform wet-out and fibre consolidation.

3.3.3 Curing

To ensure proper consolidation and reduce air voids, the laminate was cured at room temperature for 24 hours under light pressure. After curing, the panel was removed from the mould and trimmed to the required dimensions.Figure 6 to 9 shows the cured laminates front and back view with 3 mm & 5 mm thickness, respectively.

Fig. 6 Front view of the cured composite, 3 mm composite

Fig. 7 Back view of the cured composite, 3 mm composite

Fig. 8 Front view of the cured composite, 5 mm composite

Fig. 9 Back view of the cured composite, 5 mm composite

3.4 Specimen Preparation

Specimens for mechanical testing were cut from the cured composite panels according to ASTM standards. Each specimen was prepared with precise dimensions to ensure consistency in testing.

3.4.1 Tensile Test Specimens

Tensile test specimens were prepared by ASTM D3039, with dimensions of 250 mm in length and 25 mm in width. These specimens were used to evaluate the tensile strength and elongation of the composite. Figures 10 and 11 show the specimens prepared for the tensile test.

Fig. 10 Tensile test specimen- 3 mm

Fig. 11 Tensile test specimen- 5 mm

3.4.2 Flexural Test Specimens

Flexural test specimens were prepared following ASTM D790, with dimensions of 127 mm in length and 12.7 mm in width. These specimens were subjected to three-point bending tests to assess the flexural strength and stiffness of the composite. Figures 12 and 13 present the specimens prepared for the flexural test.

Fig. 12 Flexural test specimen- 3 mm

Fig. 13 Flexural test specimen- 5 mm

3.4.3 Hardness Test Specimens

For hardness testing, specimens were prepared as per ASTM D2240, with dimensions of 50 mm by 50 mm. Testing was conducted on these samples to obtain the surface hardness values of the composite material. Figures 14 and 15 present the specimens prepared for the hardness test.

Fig. 14 Hardness test specimen- 3 mm

Fig. 15 Hardness test specimen- 5 mm

3.4.4. Water Absorption Test Specimens

Specimens for water absorption testing were prepared according to ASTM D570, with dimensions of 50 mm by 50 mm. These specimens were used to measure the water absorption characteristics of the composite, which is critical for outdoor applications such as roofing. Figures 16 and 17 present the specimens prepared for the water absorption test.

Fig. 16 Water Absorption test specimen- 3 mm

Fig. 17 Water Absorption test specimen- 5 mm

3.5. Testing Procedures

The mechanical properties of the composite were evaluated through a series of tests designed to measure tensile strength, flexural strength, hardness and water absorption. All tests were conducted under controlled conditions to ensure accurate and reproducible results.

3.5.1. Tensile Testing

Tensile testing was conducted using a Universal Testing Machine (UTM) with a constant crosshead speed. The specimens were gripped at both ends and subjected to a tensile load until failure. Measurements were taken for tensile strength, modulus of elasticity and elongation at break.

3.5.2. Flexural Testing

Flexural strength was determined by the three-point bending method, where the specimen is held at two places and force is applied to the center of the specimen. Flexural strength and modulus were calculated from the load-displacement data obtained during the test.

3.5.3. Hardness Testing

The hardness of the composite material was observed using the Shore hardness test as per ASTM D2240. A Shore hardness tester was used to assess the material's indentation resistance and thus, surface hardness.

3.5.4. Water Absorption Testing

A water absorption test was performed by immersing the specimens for a determined duration. Specimens were weighed before and after immersion to measure the weight gain percentage regarding water absorption. This is an important test for evaluating the outdoor durability of the composite.

4. Results and Discussion

The results of mechanical tests on the hybrid composite materials are presented in this section. The tests include tensile strength, flexural strength, hardness and water absorption. All mechanical and physical properties reported in this study were obtained through experimental testing conducted as per relevant ASTM standards. The results are compared with the properties of conventional roofing materials such as GI, asbestos and cement to evaluate their practical suitability for roofing applications.

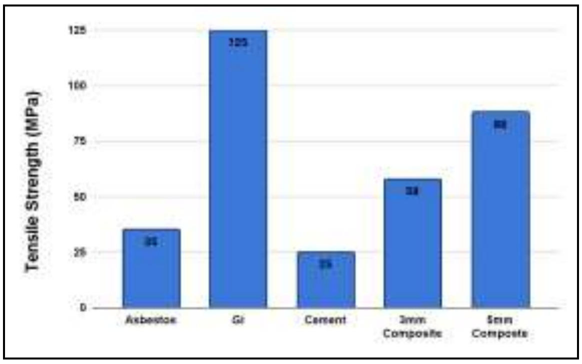
4.1. Tensile Strength

For roofing applications, tensile strength is an important property as it indicates the ability of a material to resist tensile loads without failure. Table 4 presents the tensile test results of the hybrid composite specimens with 3 mm and 5 mm thicknesses, along with a comparison to conventional roofing materials. The hybrid composite exhibited improved tensile performance due to the effective reinforcing action of banana and basalt fibres within the epoxy matrix. The 3 mm thick laminate recorded a tensile strength of 58 MPa, which is notably higher than that of asbestos and cement sheets, demonstrating its suitability for lightweight roofing applications. A further increase in tensile strength to 88 MPa was observed for the 5 mm thick laminate, attributed to the increased thickness and enhanced load-bearing capability of the composite. Although the tensile strength is lower than that of GI sheets, the composite offers significant advantages in terms of weight reduction and sustainability. The tensile strength performance of the materials is illustrated in Figure 18.

Table 4. Comparison of Tensile Strength

S.No	Materials	Tensile Strength(MPa)
1	Asbestos	20 - 38
2	GI	110 - 150
3	Cement	20 - 30
4	3 mm composite	58
5	5 mm composite	88

Fig. 18 Comparison of Tensile Strength



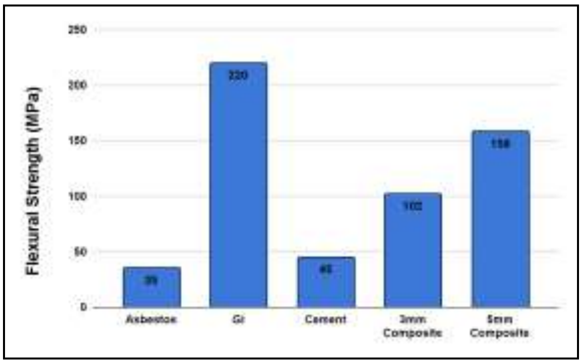
4.2. Flexural Strength

Flexural strength is a key property for roofing materials, as it reflects the ability of a panel to resist bending under applied loads. Table 5 summarizes the flexural test results of the 3 mm and 5 mm thick hybrid composite specimens, along with a comparison to conventional roofing materials. The hybrid composite demonstrated improved flexural performance compared to asbestos and cement sheets. The 3 mm thick laminate achieved a flexural strength of 102 MPa, indicating strong bending resistance despite its reduced thickness. A higher flexural strength of 158 MPa was recorded for the 5 mm thick laminate, attributed to the increased laminate thickness and improved stiffness resulting from the optimized stacking sequence. These results indicate the mechanical suitability of the developed hybrid composite under flexural loads. The comparative flexural strength performance is illustrated in Figure 19.

Table 5. Comparison of Flexural Strength

S.No	Materials	Flexural Strength (MPa)
1	Asbestos	25 - 40
2	GI	200 - 250
3	Cement	40 - 60
4	3 mm composite	102
5	5 mm composite	158

Fig. 19 Comparison of Flexural Strength



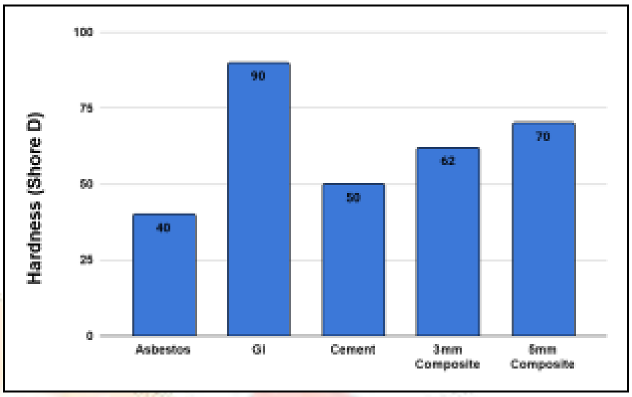
4.3 Hardness

Hardness is an important property for roofing materials, as it indicates resistance to surface wear and environmental exposure. Table 6 presents the hardness test results of the hybrid composite specimens with 3 mm and 5 mm thicknesses, along with a comparison to conventional roofing materials. The developed composite exhibited good surface hardness, which is essential for long-term durability in outdoor applications. The 3 mm thick laminate recorded a Shore D hardness value of 62, which is higher than that of asbestos sheets and comparable to GI roofing materials. A higher hardness value of 70 was observed for the 5 mm thick laminate, indicating improved resistance to surface deformation and wear. This enhanced hardness is particularly beneficial for roofing applications exposed to harsh environmental conditions. The comparative hardness performance is illustrated in Figure 20.

Table-6. Comparison of Hardness

S.No	Materials	Shore Hardness (Shore D)
1	Asbestos	31 - 50
2	GI	80 - 98
3	Cement	35 - 55
4	3 mm composite	62
5	5 mm composite	70

Fig. 20 Comparison of Hardness



4.4. Water Absorption

Water absorption is critical for roofing materials, affecting their durability and resistance to moisture-related degradation. The water absorption test details are presented in Table 7 and the test results are presented in Table 8, showing that the hybrid composite exhibits significantly lower water absorption than conventional materials. The 3 mm specimen absorbed only 1.18% of water by weight, considerably lower than asbestos and cement. This low absorption rate indicates good resistance to moisture and the potential for long-term durability in outdoor applications. The 5 mm specimen demonstrated an even lower water absorption rate of 0.73%, enhancing its suitability for roofing applications in humid or wet environments. The water absorption of the composite, measured before and after the test, is summarized in Table 8. The comparison of water absorption is shown in Figure 21.

Table-7. Comparison of Water Absorption

S.No	Materials	Water Absorption (%)
1	Asbestos	3 - 5
2	GI	0
3	Cement	12 - 18
4	3 mm composite	1.18
5	5 mm	0.73

	composite	

Fig. 21 Comparison of Water Absorption

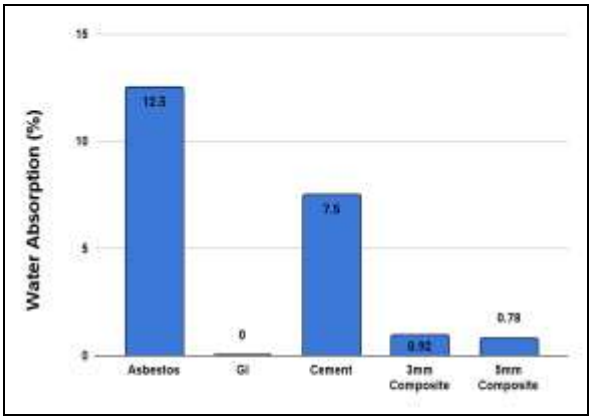


Table-8. Composite Water Absorption Details

Specimen	Initial Weight (g)	Final Weight After Immersion (g)	Water Absorbed (g)
3 mm Thick	8.50	8.60	0.10
5 mm Thick	12.30	12.39	0.09

4.5. Comparison with Conventional Roofing Materials

The mechanical performance of the hybrid composite was evaluated and compared with commonly used roofing materials such as galvanized iron (GI), asbestos sheets and cement boards. The results show that the proposed composite exhibits higher tensile strength, flexural strength and hardness than asbestos and cement-based roofing materials, while remaining lower than GI sheets but offering advantages in weight reduction, moisture resistance and sustainability. Its tensile strength surpasses that of asbestos and remains slightly below that of GI, making it suitable for components subjected to tensile loads. The composite also demonstrates greater flexural resistance than asbestos and performs reasonably close to GI, highlighting its ability to resist bending stresses.

Additionally, its hardness values are comparable to GI, ensuring good surface durability against abrasion over long-term use. The polymer matrix contributes to excellent moisture resistance, offering a clear advantage over cement and asbestos in outdoor environments where materials are continuously exposed to rain and humidity. Furthermore, the combination of Banana, Hemp and Basalt fibres is expected to contribute to improved thermal comfort when compared to metallic roofing materials such as GI, due to the non-metallic nature of the composite, thereby improving indoor comfort and reducing heat penetration through the roofing structure. These characteristics make the hybrid composite particularly suitable for lightweight roofing applications where corrosion resistance, moisture durability and sustainability are prioritized over maximum tensile capacity.

5. Implications and Potential Applications

The mechanical tests highlight the hybrid composite’s suitability for roofing use. This section explains what the results imply and how the material can be applied across various practical fields.

5.1. Implications of the Findings

The hybrid composite demonstrated improved tensile strength, flexural performance, surface hardness and significantly reduced water absorption compared to conventional roofing materials. These results indicate that the material is well-suited for applications requiring high durability and strong resistance to environmental exposure. The combination of Banana, Hemp and Basalt fibers in an epoxy matrix provides a balanced mix of strength, stability and sustainability, making it a more eco-friendly alternative to traditional roofing products.

5.2. Potential Applications

The composite's mechanical characteristics make it a strong candidate for roofing, cladding and other structural applications. Its combination of strength, durability and low water absorption supports its use in roofing systems that must withstand prolonged environmental exposure. The high flexural strength and surface hardness also make it appropriate for exterior cladding and facade panels, where long-term weather resistance is essential. In addition, its low weight and favorable strength-to-weight ratio enable its use in structural components such as lightweight walls, panels and secondary load-bearing members.

5.3. Future Research Directions

Future work can build on the strong results of this Banana-Hemp-Basalt composite by further improving the fiber-to-resin balance and exploring similar natural fibers to enhance performance even more. Additional outdoor and long-term testing will help confirm the composite's excellent durability and strengthen its potential for widespread use in roofing applications.

5.4. Broader Applications

The strong, lightweight and moisture-resistant nature of the Banana, Hemp and Basalt composite suggests it could also be used in other areas, such as lightweight panels for vehicles, outdoor structures and general construction applications.

6. Conclusion

In this study, a hybrid composite made from Banana, Hemp and Basalt fibers reinforced with an epoxy matrix was successfully developed and evaluated. The mechanical testing covering tensile strength, flexural behavior, hardness and water absorption showed that this composite performs comparably to or better than asbestos and cement-based roofing materials, while remaining lower than GI sheets. The findings confirm that the developed hybrid composite provides reliable structural performance along with improved resistance to environmental exposure, supporting its suitability for roofing and allied construction applications. The inclusion of natural fibers like banana and hemp also improves the sustainability of the material, offering an eco-friendly alternative to conventional options. The Banana, Hemp and Basalt hybrid composite demonstrates significant potential as an alternative roofing material for selected applications when compared with conventional roofing materials.

7. Environmental Impact and Sustainability Analysis

7.1. Environmental Benefits of Hybrid Composites

Using Banana, Hemp and Basalt fibers in the composite offers clear environmental advantages over traditional roofing materials. Banana and hemp are fast-growing natural fibers that require minimal water, chemicals and energy for production, making the composite more eco-friendly. Their use reduces dependence on non-renewable materials. The epoxy matrix further improves durability, extending the service life of the roofing panel and lowering the need for frequent replacements, which helps minimize overall environmental impact.

7.2. Comparison with Traditional Materials

Asbestos was once widely used for its fire-resistant qualities, but it is now recognized as a major environmental and health hazard. Its carcinogenic nature and the difficulty of safe disposal have made its use highly restricted. Cement-based roofing materials also pose environmental concerns, as cement production accounts for nearly 8% of global CO_2 emissions and requires high energy inputs while offering limited recyclability. Although GI sheets provide long service life, their manufacturing process including metal extraction and rolling demands significant energy and results in substantial greenhouse gas emissions.

In contrast, the hybrid composite developed in this study demonstrates natural fibers such as banana and hemp, which are renewable and have much lower environmental footprints. Combined with the long service life offered by the composite, the use of natural fibers contributes to reduced embodied energy and makes the material a more eco-friendly alternative to conventional roofing products.

7.3. Potential for Recycling and End-of-Life Management

Recycling the Banana, Hemp and Basalt composite can be difficult because it contains both natural fibers and a polymer matrix. However, emerging recycling methods, such as pyrolysis for recovering epoxy components and mechanical processing to reuse natural fibers show promise for improving end-of-life management and reducing environmental impact.

7.4. Sustainability Metrics

The composite's low weight reduces transportation energy, while its minimal water absorption helps lower long-term maintenance needs. The composite is expected to offer a lower environmental footprint compared to asbestos and cement roofing materials, based on fibre renewability and reduced material mass.

8. Potential Failure Modes

The composite may deteriorate due to fiber fracture, matrix cracks or fiber-matrix debonding with tensile and flexural loads. In the case of flexural loading, both buckle and tensile deflection could be observed mainly in thin specimens. Environmental factors such as moisture exposure may influence long-term performance and thermal fatigue can further compromise the composite's integrity. To reduce these risks, surface treatments, UV-resistant coatings and frequent inspections are suggested.

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