RESEARCH PAPER

Experimental Investigtion and Various Behaviours Analysis of Areca/Ramie/Coir-Natural Fiber Composites for Indutrial Application

Devaraj P[1*], Selvarasu A[2], Avinash C[3], Bhavan Kumar R[4], Guruprasath S[5] and Sivasurya K[6]

[1,2,3,4,5,6]Department of Mechanical Engineering, V.S.B. Engineering College, Karur, Tamil Nadu, India
**Corresponding Author Information: Mr.P.Devaraj*
*[1]*devarajp1992@gmail.com ORCiD : 0009-0003-9951-7201*
[2]selvarasua@gmail.com, [3]avinashank0909@gmail.com, [4]bhavankumar235@gmail.com,
[5]guruprasathsivanantham@gmail.com and [6]suryakongusiva544@gmail.com

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ABSTRACT

The development of composite materials made up of natural fibers is improving in engineering applications such as Automotive, Marine and Aerospace, due to its properties such as high specific strength, renewable, non-abrasive, low cost, biodegradability. Many researchers have identified different natural fibers used to substitute for Glass fiber, Aramid Fiber and Kevlar Fiber. Areca, Ramie and Coir Fiber are very popular and easily available along with high strength, low cost, good insulation and low thermal conductivity characteristics. For this research analysis, constant weight of matrix used as a LY 556 Grade Epoxy Resin and reinforcement is various % of Areca, Ramie and Coir Fibers. The molding process is Compression Molding Technique. The reinforcement of fibers significantly enhanced mechanical properties, including hardness, compressive strength, and flexural strength. Notably, a higher proportion of coir fibers, combined with lower proportions of Areca and Ramie fibers, results in optimal mechanical characteristics, such as elevated compressive strength, flexural strength, and impact energy, alongside a reduced level of water absorption. Furthermore, the study indicates that both hardness and tensile strength reach their peak values when a higher percentage of Areca fibers were utilized.

Keywords: *Natural Fiber Composites; Hybrid Composites; Areca Fiber; Ramie Fiber; Coir Fiber; Epoxy Resin; Compression Molding; Mechanical Properties; Water Absorption; Microstructure Analysis.*

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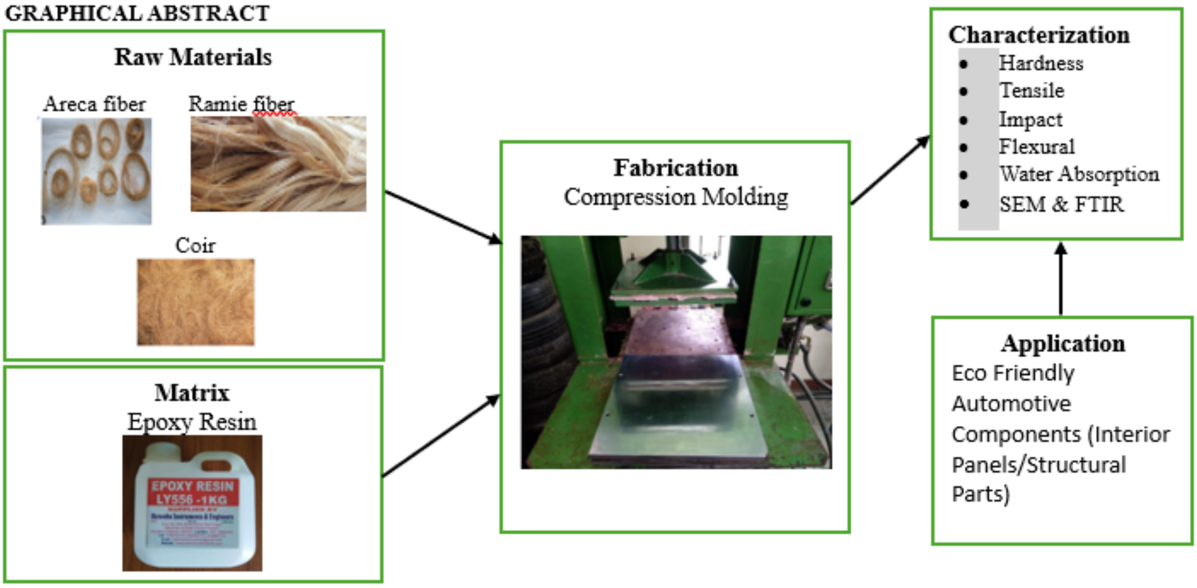
GRAPHICAL ABSTRACT



HIGHLIGHTS

- Hybrid natural fiber composites were developed using areca, ramie, and coir fibers with epoxy resin..

**Author for Correspondence: devarajp1992@gmail.com*

- Compression molding technique was used for fabrication of composite specimens.
- Higher coir content improved compressive, flexural, and impact strength with reduced water absorption.

1. INTRODUCTION

1.1 Background and Global Paradigm Shift:

In the contemporary industrial landscape, the pursuit of enhanced performance is governed by multiple criteria such as weight reduction, high strength-to-weight ratio, and cost-effectiveness. Conventional materials are increasingly reaching their performance limits, prompting researchers to develop advanced composite materials. Over the past three decades, composite materials have emerged as key engineering materials, expanding from aerospace applications to automotive, marine, and construction sectors.

In recent years, there has been a global shift toward natural fiber reinforced composites due to their advantages such as low density, renewability, biodegradability, and economic feasibility. Materials such as areca, ramie, and coir fibers offer a sustainable alternative to synthetic fibers, enabling the development of eco-friendly composites with improved mechanical performance. This transition reflects the growing emphasis on sustainable engineering materials and cost-effective manufacturing techniques for industrial applications.

1.2 Theoretical Definition and Classification of Composites:

A composite material is defined as a heterogeneous material system composed of two or more distinct constituents that differ in form and chemical composition and are insoluble in each other. In such materials, the reinforcing phase—typically in the form of natural fibers like areca, ramie, and coir—is embedded within a continuous matrix phase, such as epoxy resin. This combination enables the composite to utilize the strength and stiffness of the fibers along with the binding and protective characteristics of the matrix, thereby enhancing overall mechanical performance.

In this study, polymer matrix composites (PMCs) are utilized, where natural plant fibers act as reinforcement and epoxy resin serves as the matrix. The matrix binds the fibers, transfers load effectively, and protects them from environmental damage, while the fibers contribute significantly to tensile, compressive, and flexural strength. Natural fiber composites also follow the principle of improved strength through fiber reinforcement, while offering additional advantages such as low density, biodegradability, and cost-effectiveness. This makes them suitable for sustainable engineering applications.

1.2.1 Matrix Systems and Their Role:

The matrix in composite materials acts as a binding medium that holds the reinforcing fibers in proper orientation, transfers load through shear stress, and protects the fibers from environmental effects such as moisture, temperature variations, and chemical exposure.

- Epoxy Resins: In this study, LY 556 grade epoxy resin is used as the matrix material. Epoxy resins are widely preferred due to their high mechanical strength, excellent adhesion, thermal stability, and chemical resistance. The cross-linked polymer structure formed during curing provides strong bonding with natural fibers and enhances the overall performance of the composite.
- Thermoset Polymers: Epoxy resin belongs to the thermoset category, which cannot be remelted or reshaped once cured. Thermosets are commonly used in structural composites because of their good dimensional stability, thermal resistance, and ability to maintain properties under load. Compared to thermoplastics, they offer better bonding and structural integrity in fiber-reinforced composites.

1.3 The Rise of Natural Fiber Composites (NFCs)

India is uniquely positioned in this field due to the abundant availability of natural fibers, including Bamboo, Jute, Areca, Coir, and Ramie. The development of Natural Fiber Composites (NFCs) is driven by a dual-cleft strategy: preventing the depletion of forest resources through wood substitution and ensuring economic returns for rural cultivation.

1.3.1 Benefits of "Green" Composites:

Natural fiber reinforced composites, often referred to as "green" composites, have gained significant attention due to their eco-friendly nature and engineering advantages. In this study, composites reinforced with areca, ramie, and coir fibers exhibit the following benefits:

- Specific Strength: High specific strength and stiffness comparable to glass fibers.
- Sustainability: Natural fibers are renewable, biodegradable, and environmentally friendly. They contribute to reduced environmental impact and help in minimizing depletion of non-renewable resources.
- Economic Viability: Low-cost compared to synthetic fibers, making the composites economically attractive..

1.3.2 Chemical Complexity of Plant Fibers:

Natural fibers such as areca, ramie, and coir are complex biological materials composed mainly of cellulose, hemicellulose, and lignin. Cellulose acts as the primary structural component, providing strength and stiffness, while lignin and hemicellulose contribute to bonding and influence the overall properties of the fiber. These fibers are inherently lightweight and possess good mechanical characteristics suitable for composite reinforcement.

1.4 Hybridization: Integration of Natural Fibers:

he novelty of this research lies in the hybridization of natural fibers such as areca, ramie, and coir within an epoxy resin matrix. Different weight ratios of these fibers were combined to develop hybrid composites and evaluate their mechanical and physical behavior.

1.4.1 Role of Reinforcement Materials:
Reinforcement in the form of natural fibers plays a crucial role in enhancing the mechanical performance of composites. Fibers act as the primary load-carrying elements and significantly improve strength and stiffness of the material

- **Areca Fiber:** Contributes to higher hardness and tensile strength due to its good mechanical properties.
- **Ramie Fiber:** Provides high tensile strength and improves overall stiffness of the composite.
- **Coir Fiber:** Enhances impact, compressive, and flexural strength while also reducing water absorption in optimized ratios.

1.5 Problem Statement and Research Objectives:
Although natural fiber composites offer advantages such as low cost, biodegradability, and good mechanical properties, achieving optimal performance through proper selection and combination of fibers remains a key challenge. Limited studies are available on hybrid combinations of areca, ramie, and coir fibers, particularly in identifying the best fiber ratio for enhanced mechanical behavior and reduced water absorption. This research addresses the need for developing sustainable and high-performance hybrid composites suitable for industrial applications.

The specific objectives of this study include:

- Fabrication of epoxy-based hybrid composites reinforced with areca, ramie, and coir fibers in different weight percentages.
- Evaluation of mechanical properties such as hardness, tensile strength, flexural strength, compressive strength, and impact strength.
- Analysis of water absorption characteristics of the developed composites.
- Microstructural analysis using Scanning Electron Microscopy (SEM) to study fiber–matrix interaction and fracture behavior.

2. MATERIALS AND METHODS
The fabrication and characterization of hybrid natural fiber composites involve a systematic process, beginning with the selection of natural fibers such as areca, ramie, and coir along with epoxy resin as the matrix material. The composites were prepared using different fiber weight ratios to study their influence on mechanical and physical properties.

The specimens were fabricated using the compression molding technique under controlled temperature and pressure conditions. Standardized procedures were followed for specimen preparation and testing. Mechanical characterization was carried out through hardness, tensile, flexural, compressive, and impact tests, while water absorption behavior was also evaluated. Microstructural analysis was performed using Scanning Electron Microscopy (SEM) to examine fiber–matrix interaction and fracture behavior.

2.1 Constituent Materials and Selection:
The primary objective of material selection in this study was to develop a sustainable hybrid composite by utilizing natural fibers such as areca, ramie, and coir along with epoxy resin as the matrix. These fibers were selected due to their availability, low cost, biodegradability, and favorable mechanical properties.

2.1.1 Matrix Phase: Epoxy Resin:
A thermosetting epoxy resin (LY 556 grade) was selected as the matrix material due to its excellent mechanical strength, strong adhesion, thermal stability, and chemical resistance. Unlike thermoplastic polymers, thermoset epoxy cannot be remelted once cured and forms a rigid cross-linked structure that enhances the durability of the composite.

- **Composition:** Epoxy resin is a copolymer formed from resin and hardener components, which react to form a strong cross-linked network.
- **Hardener:** A suitable hardener is used to initiate the curing process, enabling the formation of a rigid and stable polymer structure.
- **Function:** The matrix binds the areca, ramie, and coir fibers, maintains their orientation, transfers load through shear stress, and protects them from environmental effects such as moisture and temperature variations..

2.1.2 Reinforcing Phase: Natural Fibers:

- **Areca Fiber:** Obtained from the areca plant, this fiber exhibits good tensile properties and contributes significantly to hardness and tensile strength of the composite. Its availability and eco-friendly nature make it suitable for reinforcement
- **Ramie Fiber:** A bast fiber known for its high tensile strength and stiffness, ramie enhances the overall mechanical performance and structural stability of the composite.
- **Coir Fiber:** Extracted from the coconut husk, coir fiber is characterized by low density, good impact resistance, and high durability

Areca fiber

Ramie fiber

Coir fiber

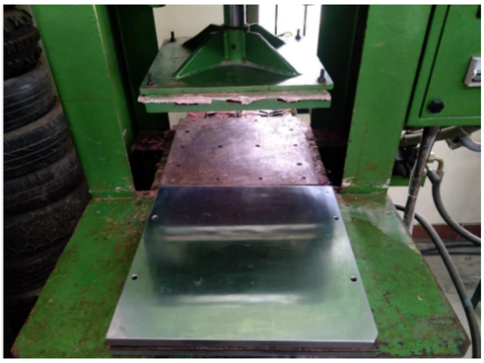
2.1.3 Composite Formulation (Fiber Ratios)
To enhance the mechanical performance of the composite, different weight percentages of natural fibers were incorporated into the epoxy matrix. Three hybrid combinations were developed to study the effect of fiber variation:

- **R1:** Higher areca fiber content with lower ramie and coir proportions, aimed at improving hardness and tensile strength.
- **R2:** Higher ramie fiber content with balanced areca and coir, contributing to improved stiffness and strength**.**
- **R3:** Higher coir fiber content with lower areca and ramie, enhancing impact, compressive, and flexural properties while reducing water absorption.

2.2 Formulation of Hybrid Ratios
The experimental design utilized a matrix–reinforcement ratio in which the epoxy resin was kept constant at **200 grams**. Three distinct hybrid ratios (R1, R2, R3) were prepared by varying the weight percentages of areca, ramie, and coir fibers to study their combined effects on mechanical and physical properties:

Component	Ratio 1 (R1)	Ratio 2 (R2)	Ratio 3 (R3)
Epoxy Resin (ER)	200 gm	200 gm	200gm
Areca Fiber (AF)	20%	5%	5%
Ramie Fiber (RF)	5%	20%	5%
Coir Fiber (CF)	10%	7.5%	5%

2.3 Fabrication Process: Compression Moulding
The composites were fabricated using a hydraulic compression molding technique, which is widely preferred for its simplicity, high reproducibility, and low cycle time. This method enables the production of uniform composite sheets with good fiber distribution and reduced porosity.



1. **Mold Preparation:** A metal die of size **290 × 290 mm** was cleaned and prepared to ensure proper moulding and easy removal of the composite sheet.
2. **Mixing:** The calculated weights of areca, ramie, and coir fibers were combined with epoxy resin. The resin was mixed with accelerator and catalyst (approximately 4% and 1%) to initiate the curing process.
3. **Filling**: The prepared fiber–resin mixture was poured into the mold and evenly distributed to ensure uniform reinforcement.s.
4. **Pressing:** A motorized hydraulic compression moulding machine was used to apply pressure, ensuring proper compaction and bonding of the composite.
5. **Curing:** The mould was heated using electric heaters, and the composite was allowed to cure for a specified time to form a solid plate, which was then removed and cut into test specimens.

2.4 Mechanical Testing Protocols

Standardized testing was conducted to evaluate the structural integrity and durability of the fabricated specimens.

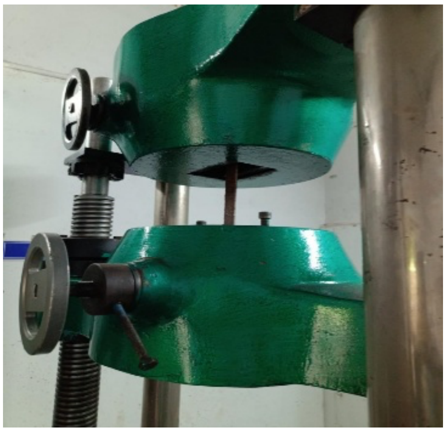
2.4.1 Hardness Testing (Shore-D)

Surface hardness was measured using a Shore-D Durometer according to ASTM D2240 standards. This test evaluates the resistance of the composite to indentation, which is a critical parameter for automobile structural components.

2.4.2 Tensile Strength and Elongation

Tensile properties of the fabricated composite specimens were evaluated using a Universal Testing Machine (UTM).

- **Specimen Preparation:** Samples were prepared and cut into standard dimensions suitable for tensile testing.
- **Measurement:** The UTM applied an axial load until fracture, recording the maximum tensile strength (N/mm²) and the percentage of elongation at break.



2.4.3 Impact and Flexural Strength

- **Impact Test:** The impact strength of the composite specimens was evaluated using a low-energy impact testing setup. This test measures the energy absorbed by the material during fracture and indicates its toughness and resistance to sudden loads**.**
- **Flexural Strength Test:** The flexural properties were determined using a standard bending test, where the specimen was supported and a load was applied until failure. This test evaluates the bending strength and stiffness of the composite material.

2.4.4 Water Absorption Evaluation

Since natural fibers are hygroscopic in nature, the fabricated composite specimens were subjected to water absorption testing. The samples were immersed in water for a specific duration, and their weight was measured periodically to evaluate the percentage of water absorption. This test helps in analyzing the moisture uptake behavior and its effect on dimensional stability and performance of the composites.

3. MECHANICAL CHARACTERIZATION

The mechanical characterization of hybrid natural fiber-reinforced composites is essential to evaluate their strength, stiffness, and durability for engineering and industrial applications. This section presents the experimental procedures used to determine hardness, tensile strength, flexural strength, compressive strength, impact resistance, and water absorption behavior of the fabricated specimens. Standard testing methods were followed to ensure reliable and consistent results for performance evaluation.

3.1 Shore-D Hardness Evaluation

Hardness is an important mechanical property that indicates the resistance of a material to surface indentation and wear. For natural fiber-reinforced epoxy composites, hardness testing helps in understanding the effect of fiber content and distribution on surface strength and durability.

3.1.1 Principles of Shore-D Testing

The Shore-D hardness test is used for harder polymer composites. It employs a durometer with a hardened indenter to measure the resistance of the specimen surface.

- **Testing Procedure:** The specimen is placed on a flat surface, and the durometer is applied without impact. The hardness value is recorded after proper contact with the specimen surface.
- **Significance in This Study:** The variation in fiber composition (areca, ramie, and coir) influences the hardness of the composite. Higher areca fiber content was observed to improve hardness, indicating better resistance to surface deformation.

3.2 Tensile Property Analysis

Tensile testing is a fundamental mechanical characterization used to determine the strength and deformation behavior of the hybrid natural fiber composite. It provides important information about tensile strength and elongation, indicating the ability of the material to withstand axial loads before failure.

3.2.1 Sample Geometry and Instrumentation

Tensile testing was carried out using a Universal Testing Machine (UTM). The specimens were prepared in standard dimensions suitable for tensile testing to ensure accurate and consistent results. The test was performed by applying axial load until fracture, ensuring that failure occurred within the specimen gauge section.

3.2.2 Key Performance Indicators

- **Tensile Strength**: Represents the maximum stress the composite can withstand before failure. It depends on the effective bonding between the natural fibers (areca, ramie, and coir) and the epoxy matrix.
- **Stiffness (Strength Behavior):** Indicates the ability of the composite to resist deformation under load, influenced by fiber type and composition**.**
- **Percentage Elongation:** Measures the deformation of the material before fracture, indicating the ductility of the composite.

3.3 Impact Resistance and Toughness
Impact testing is used to determine the energy-absorbing capacity of the composite under sudden loading conditions. It indicates the toughness of the material and its ability to resist fracture.

3.3.1 The Impact Test Method
The impact strength of the specimens was evaluated using a low-energy impact testing setup.

- **Energy Absorption:** The test measures the amount of energy absorbed by the specimen during fracture, expressed in terms of impact energy.
- **Significance in This Study:** The presence of natural fibers, especially coir, improves the toughness of the composite. Fiber bridging and pull-out mechanisms help in absorbing more energy, thereby enhancing impact resistance

3.4 Flexural and Bending Strength (ASTM D790)
Flexural testing is used to evaluate the bending strength and stiffness of the composite material under load. It helps in understanding the ability of the material to resist deformation when subjected to bending forces..

3.4.1 Flexural Test:
In this test, the specimen is supported and a load is applied until failure occurs..

- **Flexural Modulus:** Indicates the maximum stress the material can withstand before bending failure.
- **Significance in This Study:** The flexural properties are influenced by the type and proportion of natural fibers. Higher coir content was observed to improve flexural strength due to better load distribution and resistance to deformation.

3.5 Water Absorption and Environmental Stability (ASTM D570)
Natural fibers such as areca, ramie, and coir are hygroscopic in nature due to the presence of cellulose, which leads to moisture absorption. This property influences the durability and dimensional stability of the composite.

3.5.1 Water Absorption Test
To evaluate the moisture behavior of the composite, specimens were immersed in water for a specific duration and periodically weighed to determine the percentage of water absorption.

- **Water Absorption Behavior:** Moisture enters through the fiber–matrix interface, leading to swelling and possible reduction in mechanical properties..
- **Significance in This Study**: Composites with higher coir content showed reduced water absorption, indicating better resistance to moisture and improved environmental stability**.**

4. RESULTS AND DISCUSSION
The experimental results of the hybrid natural fiber composites are discussed with emphasis on the effect of varying weight percentages of areca, ramie, and coir fibers in the epoxy matrix. The analysis focuses on the mechanical properties such as hardness, tensile strength, flexural strength, compressive strength, impact strength, and water absorption behavior. The influence of fiber composition and distribution on the overall performance of the composites is also evaluated.

4.1 Comparative Analysis of Mechanical Performance

The mechanical behavior of the three hybrid ratios (R1, R2, and R3) was evaluated through various tests, showing distinct variations based on the proportion of areca, ramie, and coir fibers.

4.1.1 Hardness Behavior
Surface hardness, measured using the Shore-D method, is an important parameter indicating resistance to surface deformation

- **Maximum Hardness:** The composite with higher areca fiber content (R1) exhibited the highest hardness value.
- **Discussion:** The increased hardness in R1 is attributed to the higher percentage of areca fiber, which enhances surface strength and resistance to indentation.
- **Trend:** As the areca fiber content decreases in other ratios, a reduction in hardness is observed, highlighting the influence of fiber composition on surface properties.

4.1.2 Tensile Strength and Elongation
Tensile testing was conducted to evaluate the load-bearing capacity of the hybrid composites under axial loading conditions.

- **Peak Performance:** The composite with higher areca fiber content exhibited the maximum tensile strength.
- **Comparative Values:** Other ratios showed relatively lower tensile strength due to variation in fiber composition..
- **Discussion:** The results indicate that tensile strength is strongly influenced by effective fiber–matrix bonding

and fiber type. Higher areca fiber content improves tensile properties, while increased coir content tends to reduce tensile strength due to its lower stiffness.

4.1.3 Impact Energy and Toughness

The ability of the material to absorb energy during sudden loading was assessed using the Izod impact test.

- **Findings:** The composite with higher coir fiber content (R3) exhibited higher impact energy compared to other ratios.
- **Discussion:** The improved impact strength is attributed to the presence of coir fibers, which enhance toughness through fiber pull-out and crack-bridging mechanisms. These mechanisms absorb more energy during fracture and prevent sudden failure of the composite.

4.1.4 Flexural and Compressive Strength

- **Flexural Strength:** The composite with higher coir fiber content (R3) exhibited improved flexural strength, indicating better resistance to bending loads. This is due to effective load distribution and enhanced toughness provided by coir fibers.
- **Compressive Strength:** Similarly, R3 showed higher compressive strength compared to other ratios. The presence of coir fibers contributes to better load-bearing capacity under compression.
- **Discussion:** The results indicate that increasing coir fiber content enhances both flexural and compressive properties, making the composite more suitable for structural applications.

4.2 Environmental Stability: Water Absorption

Due to the hygroscopic nature of natural fibers, water absorption is an important factor affecting the durability of the composite..

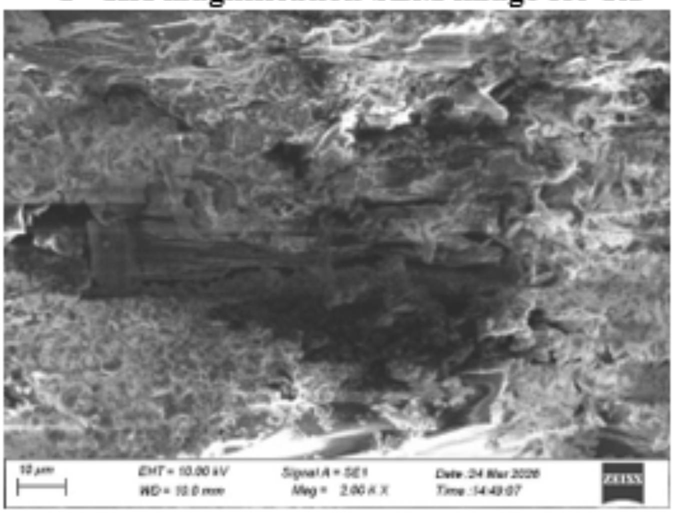
- **Observations:** Water absorption tests showed that different fiber ratios influence the moisture uptake behavior of the composites. Composites with higher coir fiber content exhibited lower water absorption compared to other combinations.
- **Discussion:** The epoxy matrix reduces moisture penetration by binding the fibers and limiting direct exposure to water. Improved fiber–matrix bonding helps in minimizing swelling and enhances the environmental stability of the composite..

4.3 Microstructural Analysis (SEM)

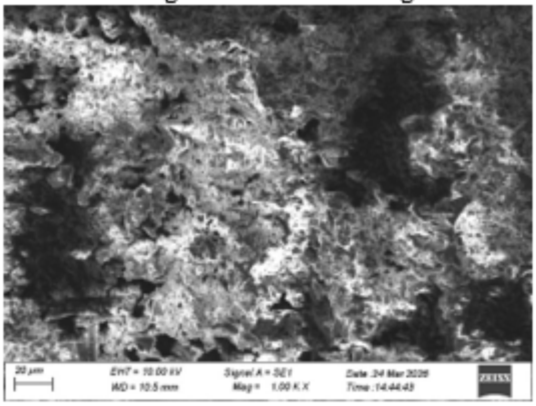
Scanning Electron Microscopy (SEM) was used to analyze the fracture surfac.

- **Ratio R1:** SEM images showed fiber–matrix bonding with some fiber pull-out, indicating the influence of higher areca fiber content on hardness and tensile behavior.
- **Ratio R2:** The microstructure revealed relatively uniform fiber distribution and improved interfacial bonding, contributing to better overall mechanical performance.
- **Ratio R3:** SEM analysis indicated the presence of coir fibers with good energy absorption characteristics, along with some voids and fiber pull-out affecting strength.

1 - KX magnification SEM image for-R1

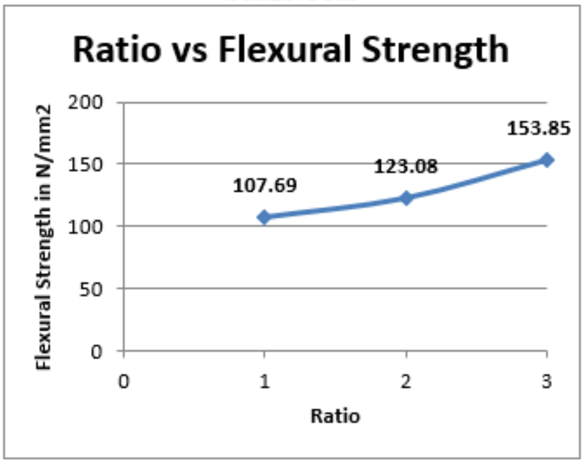


2 - KX magnification SEM image for-R2

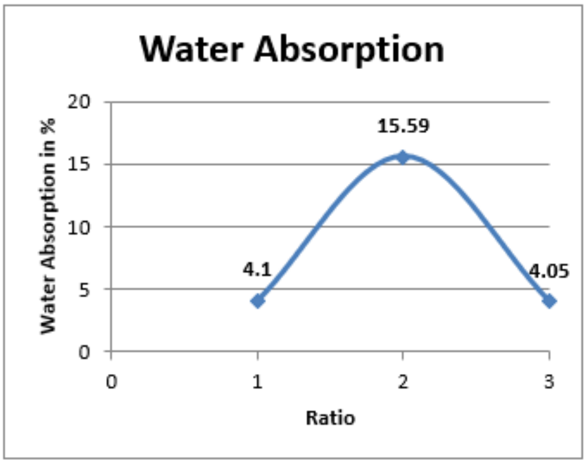


- **Common Observations:** Fiber pull-out, matrix cracking, and minor voids were observed, which are typical failure features in natural fiber composites under loading conditions.

GRAPHICAL REPRESENTATION FLEXURAL STRENGTH



GRAPHICAL REPRESENTATION WATER ABSORBTION



5. CONCLUSION AND FUTURE SCOPE

5.1 Conclusion

The investigation into hybrid natural fiber reinforced composites (NFRC) utilizing Areca, Ramie, and Coir fibers integrated into an epoxy resin matrix has led to the following findings:

- **Optimal Fiber Ratios for Durability:** A higher proportion of **Coir fibers (20%)**, combined with lower proportions of Areca and Ramie fibers (5% each), results in optimal mechanical characteristics, including the highest **compressive strength (4 N/mm²)**, **flexural strength (153.85 N/mm²)**, and **impact energy (4.11 J)**.

- **Peak Strength Performance:** Hardness and tensile strength reach their maximum values when a higher percentage of **Areca fibers (20%)** is utilized. Specifically, this ratio (R1) achieved a **Shore-D hardness of 63** and a **tensile strength of 10.13 KN** (noting a discrepancy in the results section where 57.87 N/mm² is mentioned as the induced strength).
- **Moisture Resistance:** The study demonstrated that Ratio R3 (high Coir content) and R1 (high Areca content) exhibit the lowest water absorption rates, at **4.05%** and **4.1%** respectively, over a 72-hour period.
- **Microstructural Integrity:** SEM analysis confirmed that while the composites show good fiber dispersion, high Ramie content (Ratio R2) can lead to inadequate adhesion and localized porosity, whereas high Coir content (Ratio R3) results in minimal delamination.
- **Sustainability:** The project successfully demonstrates that natural plant fibers can serve as effective, low-cost, and environmentally friendly substitutes for synthetic reinforcements in engineered materials.

5.2 Future Scope

While this research establishes a strong foundation for hybrid natural fiber composites, the following areas are suggested for future exploration:

- **Surface Modifications:** Further investigation into chemical treatments (such as advanced alkali or benzoylation) could be explored to further minimize non-cellulose components like lignin and wax, thereby improving the fiber-matrix interfacial bonding.
- **Thermal Stability Optimization:** Given that Areca fibers are thermally stable up to **230°C**, future work could focus on hybridizing these with other high-temperature resistant bio-polymers to expand their application in high-heat environments.
- **Expanded Hybridization:** Testing different combinations of the diverse natural fibers available in India—such as Bamboo, Jute, or Pineapple—could reveal even more cost-effective wood substitutes for the housing and building sectors.
- **Long-term Durability Studies:** Future research should address the biological decay of these "green" composites when exposed to light and high humidity over extended periods to improve their service life.

6. REFERENCES

The following references are formatted according to the conventions observed in the reference journal paper, ensuring academic rigor and proper citation of the foundational works utilized in this study.

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