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Design and Development of Interlocked Coir Composite Coconut Fiber Composite Materials Using Vacuum Bagging method

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Abstract

This study explores the design, fabrication, and characterization of coir fiber reinforced composites using CNSL modified epoxy resin. Composite variants interlocked untreated were fabricated using compression molding with a 1:1.25 epoxy-to-hardener ratio and 15-20% CNSL. Mechanical testing (tensile, flexural, impact), along with FTIR, TGA, and SEM analyses, evaluated structural and thermal properties. Results indicate that interlocked coir composites exhibited superior mechanical strength, while CNSL enhanced impact resistance and thermal stability. However, excessive mercerization reduced impact toughness. The findings highlight coir fiber composites as sustainable alternatives for automotive, aerospace, and construction applications. Future research can optimize biodegradability and fiber loading to enhance performance.

Keywords: Coir fiber composite, CNSL, epoxy resin, sun light dried mercerization, mechanical properties, FTIR, SEM, TGA.

1. Introduction

The need for ecologically friendly and sustainable materials has increased significantly in recent years due to worries about climate change, resource depletion, and environmental deterioration[1]. Conventional composite materials are frequently reinforced with synthetic fibers. such as glass and carbon, offer high strength and durability. However, they come at a cost: high energy consumption during production, limited biodegradability, and negative environmental impacts[2]. As a result, research has increasingly focused on developing 'green' composites, which utilize natural fibers and biodegradable or bio-based matrices to offer a viable alternative with lower ecological footprints.

Among the various natural fibers available, coir fibers have attracted attention due to their unique properties and abundance. Coir, derived from the husk of coconuts[3], is a ligno cellulosic fiber known for its high lignin content, excellent durability, and natural resistance to rot, moisture, and fungal attacks[4]. These characteristics make coir fibers a promising candidate for reinforcement in composites. However, coir fibers also have limitations, such as relatively high stiffness and lower mechanical properties compared to other natural fibers like jute or flax[5]. Researchers have investigated changes to enhance coir bonding ability and overall performance inside composite matrices in order to address these issues.

In this context, the development of coir-reinforced composites involves enhancing the fiber's interfacial bonding with the matrix through various treatments and the incorporation of additives. One common approach is the mercerization of fibers[6], where coir fibers are treated with sunlight to improve surface roughness and increase bonding potential. For further improvements in composite strength and durability, cashew nut shell liquid (CNSL) and liquid rubber are incorporated into the composite matrix. These components function as binders and toughening agents, creating a stronger and more resilient material.

Fig. 1. *Interlocked coir fiber composite material.*

The fabrication process for such composites typically involves creating a multi-layered structure in which coir mats and the epoxy-hardener mixture are alternately placed and compressed[7]. The application of CNSL and liquid rubber ensures better cohesion between the coir layers and matrix, resulting in improved mechanical qualities. The resulting coir reinforced composites demonstrate enhanced impact resistance, flexural modulus, and tensile strength compared to untreated counterparts, making them suitable for a wide variety of uses. Potential uses comprise building supplies, automobile parts, packaging, and furniture, where sustainability, lightweight, and strength are desirable attributes.

This study focuses on developing coir-reinforced composites through the sequential layering of treated coir mats and epoxy-hardener mixtures with CNSL, followed by compression molding. Analyzing how these treatments affect the composite's mechanical performance is the goal under tensile loading and other conditions. By combining natural fibers with innovative treatment methods[8], The goal of this study is to advance the field of green composite technology, promoting environmentally responsible alternatives for diverse industries.

The treatment process includes dried the coir fibers under sun light-controlled conditions of concentration and duration. This process not only enhances the fiber-matrix interaction but also modifies the fiber's interior structure, increasing the degree of cellulose crystallinity and reducing the moisture absorption capability. Consequently, sun light treated coir fibers exhibit better rigidity and tensile strength in contrast to untreated fibers, making them more suitable for structural applications[9].

In the formulation of the processed coir fibers are used in coir-reinforced composites are converted into mats that serve as reinforcement layers. To fabricate the composite, a matrix material, typically an epoxy resin, is mixed with a hardener in a specific ratio (in this case, 1:1.25). To further enhance the composite's properties[10], cashew nut shell liquid (CNSL) and liquid rubber are incorporated into the matrix. CNSL is a phenolic chemical that is a byproduct[11] of the cashew industry known for its binding properties and ability to enhance the toughness of polymer matrices[12]. Liquid rubber, Conversely, acts as a toughening agent, improving the composite's pliability and resilience to impact. Together, these additives [13]create a matrix that can effectively distribute stress and enhance the finished composite material's overall mechanical qualities.

The fabrication of coir-reinforced composite material involves a systematic layering technique using sunlight dried -treated coir mats and an epoxy-hardener matrix modified with cashew nut shell liquid (CNSL) and liquid rubber. This process ensures enhanced mechanical properties[14] and environmental benefits compared to untreated counterparts[15].

To fabricate the composite, a compression molding technique is employed. The process begins by preparing the coir fibers, which are treated under sunlight to improve adhesion and mechanical integrity. The treated fibers are then arranged into mats and layered alternately with the epoxy-hardener mixture within the mold. The epoxy- hardener system is precisely mixed at a 1:1.25 ratio, incorporating 20% CNSL as an additive to enhance toughness and durability. Each layer of coir mat is carefully positioned and infused with the resin to ensure uniform impregnation and bonding[16]. Once all layers are placed, the multi-layered structure undergoes compression molding, applying controlled pressure to achieve a dense and cohesive composite with minimal voids.

The resulting composite exhibits superior mechanical characteristics, including enhanced tensile strength, flexural rigidity[17], and impact resistance[18]. The synergy between sunlight dried - treated coir fibers and the CNSL-modified matrix significantly improves the material's load-bearing capacity while maintaining its lightweight nature. The inclusion of liquid rubber further enhances toughness and resistance to crack propagation, making the composite a durable and resilient alternative to conventional materials.

This coir-reinforced composite finds extensive use in a variety of industries, such as packaging, construction materials, and automotive components. Its biodegradability, lightweight nature, and improved mechanical performance make it a promising sustainable alternative to synthetic fiber composites[19]. By optimizing fiber treatment[20] and matrix modification, this research contributes to the advancement of green composite technologies, demonstrating Coir fiber's potential as an environmentally friendly reinforcing material for upcoming advancements[21]. The development of such composites aligns with global sustainability efforts, reducing dependence on non-renewable materials and promoting environmentally responsible engineering solutions[22].

2. Objective

Developing and evaluating a coir fiber-reinforced composite material with Cashew Nut Shell Liquid (CNSL) as an additive to improve its mechanical and thermal properties[14], [23] is the main goal of this research.

This research aims to:

- Improve Mechanical Properties: Fiber treatment and resin optimization can increase tensile, flexural, and impact strength.
- Investigate CNSL Effectiveness: Evaluate the role of CNSL in improving bonding and thermal stability[24].
- Optimize Mercerization Treatment: Study the impact of sunlight dried treatment on fiber-matrix adhesion.
- Conduct Mechanical and Thermal Testing: Perform Tensile Testing, SEM (Scanning Electron Microscopy), FTIR (Fourier Transform Infrared Spectroscopy), and Thermal Analysis to evaluate structural integrity, chemical composition[25], and heat resistance.
- Promote Sustainability: Develop an eco-friendly composite material with potential industrial applications[26].

3. Methodology

This section outlines the preparation and characterization of three different composite specimen to evaluate the impact of fiber treatment, CNSL addition, and interlocking fiber structure.[27]

Fig 2. The process of treating coconut husk into fiber.

3.1 Specimen Details

The composite specimens were prepared and analyzed:

Interlocked Coir Composite - Coir fibers arranged in an interlocked structure to improve the mechanical properties and load distribution.

Each specimen underwent fabrication, testing, and analysis to compare its mechanical strength, thermal stability, and chemical composition.

3.2 Sample Preparation

3.2.1 Composite Fabrication

Two specimens were fabricated using the vacuum bagging method to ensure uniform resin impregnation and fiber wetting and one was made using compression mould. **Interlocked Coir Composite:**

- The coir fibers were woven and interlocked in a crisscross pattern to form a structured fiber network. The epoxy-CNSL mixture was infused between the layers to bind the interlocked fibers.
- The compression Mould technique was used to enhance resin penetration and minimize voids.

3.3 Testing and Characterization

Each composite specimen was subjected to mechanical, chemical, and thermal analysis to

determine how fiber treatment, CNSL addition, and interlocking structure affect performance.

4. Mechanical Testing

4.1 Tensile Strength Test

Assessing the coir fiber reinforced composite's strength and stiffness under tensile stress was the aim of the tensile test. A Standard Universal Testing Machine (UTM) was used for the test, guaranteeing accurate and consistent measurements. Because the elimination of lignin and hemicellulose enhanced fiber-matrix adhesion, it was anticipated that the sunlight dried - treated composite would have a better tensile strength than the untreated composite. Furthermore, because of improved load distribution and improved fiber interlocking, which aids in preventing deformation under applied stress, it was expected that the interlocked fiber composite would exhibit superior tensile qualities.

4.2 Flexural Strength Test

Determining the composite's structural stiffness and assessing its resistance to bending forces were the goals of the flexural test. To ensure precise measurement of the material's resistance to bending stress, the test was carried out on a flexural testing equipment with a three-point bending configuration. It was expected that the interlocked fiber composite would exhibit the highest flexural strength compared to both the untreated and sun light dried - treated composites. This is due to the interwoven fiber network in the interlocked composite, which enhances load distribution and prevents premature failure under bending stress.

4.3 Impact Strength Test

Assessing the composite's capacity to absorb and release energy under abrupt loading circumstances was the aim of the impact test. A standardized impact testing apparatus was used for the test, guaranteeing an accurate assessment of the material's toughness. It was expected that the interlocked fiber composite would exhibit the highest impact strength[28], as its structured fiber arrangement allows for better energy dissipation and resistance to sudden

forces[29]. In contrast, the untreated and sun light dried - treated random fiber composites were anticipated to have lower impact resistance, as their unstructured fiber alignment may lead to inefficient energy absorption and increased chances of brittle failure.

4.4 Chemical Analysis.

4.4.1 **Fourier Transform Infrared Spectroscopy (FTIR)** Finding chemical changes in coir fibers and assessing resin-fiber interactions in the composite were the goals of the FTIR investigation. This technique helps identify functional groups present in the material, providing insights into changes due to sun light dried treatment and fiber arrangement. It was expected that the sun light dried - treated composite would exhibit reduced peaks corresponding to lignin and hemicellulose, confirming the successful removal of surface impurities and improved fiber reactivity. Additionally, the interlocked fiber composite may display distinct resin-fiber bonding characteristics, as its structured fiber arrangement could influence the distribution and penetration of the epoxy resin, affecting the overall chemical interactions within the material.

4.5 Microstructural Analysis.

4.5.1Scanning Electron Microscopy (SEM)

The objective of the SEM analysis was to observe fiber-matrix bonding and evaluate the microstructural integrity of the coir fiber-reinforced composite, including void formation, fiber pull-out, and adhesion quality. It was expected that the untreated composite would exhibit poor adhesion, with visible fiber pull-out and gaps at the fiber- matrix interface, indicating weak bonding. In contrast, the sun light dried - treated composite was anticipated to show improved fiber-matrix interaction, as the removal of lignin and hemicellulose creates a rougher fiber surface, enhancing mechanical interlocking. Additionally, the interlocked composite was expected to display densely packed fibers with minimal voids, contributing to stronger mechanical performance and improved load transfer within the material[30].

4.6 Thermal Analysis.

4.6.1 Thermogravimetric Analysis (TGA)

The purpose of the TGA analysis was to evaluate the composite's heat stability and degradation behavior. Because hemicellulose and lignin were sun light dried eliminated, it was anticipated that interlocking and -treated composites would exhibit greater heat stability than untreated samples. Since the interlocked composite's organized fiber arrangement

improves stability and slows degradation, it was expected to offer superior heat resistance.

5. Development of coconut fiber impregnated composite material

5.1 Materials and Methods

Three bio-based epoxy matrices were prepared for the composite specimens using Araldite AW106 epoxy resin mixed with CNSL at 15 wt% and 20 wt% concentrations. CNSL was incorporated as a reactive bio-based additive to enhance flexibility, impact strength, and thermal resistance while promoting environmental sustainability.

The epoxy-CNSL blends were combined with HV 953 hardener at a 1:1.25 ratio (hardener to resin) to ensure optimal curing, balancing mechanical strength and flexibility for composite applications. These matrices were then used to fabricate the composite specimens:

Interlocked untreated coir fiber composite – Fabricated using compression molding.

5.2 Coir Fiber Preparation and Treatment

Coir fibers act as reinforcement in the composite and undergo multiple stages of cleaning and treatment before fabrication:

Cleaning Process: To eliminate dust, debris, and undesirable surface contaminants, fibers are carefully cleaned with distilled water. This removes any bonding obstacles, improving fiber-matrix adhesion.

Drying: Washed fibers are sun-dried for 24–48 hours to ensure adequate moisture removal, which is crucial for effective resin impregnation.

Mercerization Treatment: A subset of fibers undergoes sunlight treated to modify their surface. This treatment removes lignin and hemicellulose, increases cellulose exposure, roughens the fiber surface, and improves interfacial bonding with the epoxy matrix.

Post-Treatment Neutralisation: Before being used in the creation of composites, mercerized fibers are thoroughly cleaned with distilled water to get rid of extra alkali and allowed to dry outside.

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5.3 Composite Fabrication Process:

Fig. 3. Interlocked Coir.

Three different coir-based composite specimens were fabricated using vacuum bagging for untreated and treated specimens, and compression molding for the interlocked specimen:

Interlocked Coir Fiber Composite (Untreated – Compression Molding):

- Coir fibers were arranged in an interlocked pattern to enhance fiber interlocking and mechanical interfacial bonding.
- On the mold, a thin coating of CNSL-epoxy resin was placed.
- The interlocked coir mat was placed inside, and additional layers of resin were poured over it.
- A compression force was applied to compact the fiber layers and improve resin penetration.
- The mold was clamped and cured under controlled temperature and pressure conditions.

Composition of Materials Used:

Sample No	Fiber Type	Fiber Tretment	Fiber Arrangement	Fiber Weight (g)	Epoxy Resin(g)	CNSL(g)	Hardene r(g)	Total Weigh t(g)
Interlo cked Treate d coir	Coir Fiber	Untreated	Interlocked	50	133.34	33.4	133.34	350

Table no. 1. Composition of Materials Used.

5.4 Compression Mould Process (Interlocked coir fiber specimen):

The interlocked coir fiber specimen was fabricated using the compression moulding process. By ensuring even resin distribution and efficient coir fiber impregnation, this technique improves the composite's mechanical qualities. The following steps were part of the process:

1. **Preparation of Coir Fiber Mat**

- Coir fibers were interlocked and arranged into a structured mat to improve fiber bonding and load distribution.

2. **Application of Resin System**

- The epoxy resin and CNSL mixture was prepared in the required ratio.
- After inserting the interlaced coir fiber mat into the mold, the resin mixture was evenly spread across the mat.

3. **Layering and Mould Placement**

- Additional layers were placed as per the required thickness.

- The top mould plate was positioned to apply uniform pressure.

4. **Compression and Curing**

- The mould assembly was placed under a hydraulic press.
- A specific pressure was applied to ensure proper resin penetration and fiber bonding.
- The specimen was left to cure under controlled conditions to achieve the final composite structure.

Fig.4. *Prepared mould for specimen fabrication*

Fig.5. Pouring the resin mixture (Epoxy - CNSL) into the mould

Fig. 6. Spreading the resin evenly inside the mould before fiber placement.

Fig.7. Placement of interlocked coir fiber mat inside the mould.

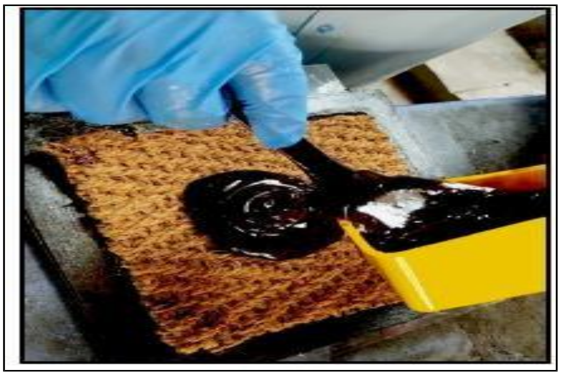


Fig. 8. Pouring the CNSL modified epoxy resin onto the coir mat.

Fig. 9. Spreading the resin uniformly ever the coir mat.

Fig. 10. Addition of a release film over the rein-coated fiber mat.

Fig.11. Compression molding setup with a hydraulic press applying pressure.

Fig. 12. Demolding of the composite specimen after compression molding using a hydraulic press.

5.4.1 Controlled Curing Conditions

- Temperature & Pressure Control: Curing was conducted under room temperature (avg 23-28°C) and pressure conditions, ensuring complete polymerization.
- Resin Infiltration Optimization: Uniform pressure across the mold eliminated air voids and ensured dense composite formation.

5.4.2 Importance of Curing Time.

- Shorter curing times lead to incomplete polymerization, weakening the composite.
- Excessive curing causes thermal stress, affecting durability.
- Optimized curing conditions provide the best balance of mechanical performance

6. Testings

Importance of Mechanical and Thermal Testing in Coir Fiber Reinforced Composites

The mechanical and thermal testing of coir fiber reinforced composites plays a crucial role I understanding their strength, durability, and suitability for real-world applications. These test help in evaluating the effects of fiber treatment, CNSL composition, and fabrication techniques on composite performance. Below is an elaboration on the importance of each test conducted.

6.1 Importance of Tensile Testing (ASTM D3039)

Tensile testing determines how much stress a material can bear before breaking when stretched. Because fiber- reinforced composites are used in load-bearing applications, this is very crucial.

Determines Tensile Strength: Helps in evaluating how well the composite resists pulling forces, which is essential in applications involving structural loads.

Influence of Fiber Treatment: Provides insight into how sun light dried treatment improves fiber matrix adhesion, thereby increasing tensile strength.

Effect of CNSL on Resin Behavior Since CNSL-modified epoxy increases flexibility, tensile testing helps analyze whether higher CNSL content improves or weakens tensile performance.

Predicting Structural Reliability: Ensures that the composite can withstand expected operational stresses in automotive, aerospace, and construction applications and material stability.

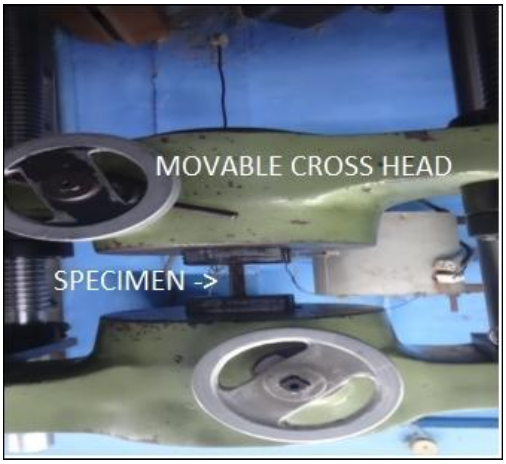


Fig. 13. Tensile Testing: This represents the tensile strength test performed on the composite specimen.

6.2 Importance of Flexural Testing (ASTM D7264)

Flexural testing determines the stiffness and bending resistance of the composite material by applying a force at the center while the material is supported at both ends (Three-Point Bending Test).

- **Evaluates Composite Rigidity:** Measures the flexural modulus, which indicates how much the material bends under load.
- **Importance in Structural Components:** Essential for materials used in beams, panels, and furniture, where bending resistance is crucial.
- **Fiber-Matrix Adhesion Assessment:** The material's resistance to deformation is increased by a strong fiber- matrix connection. Premature failure is the result of poor bonding.
- **Effect of Interlocked vs. Random Fiber Arrangements:** Helps compare whether interlocked fiber composites have superior flexural properties[31] over randomly arranged ones.

Fig. 14. Flexural Testing: Corresponds to the three-point bending test used to evaluate the flexural strength.

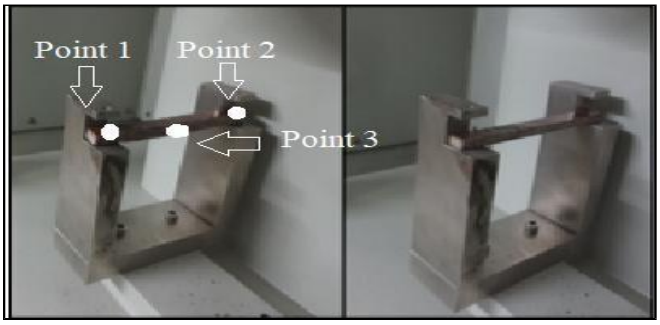


Fig. 15. Impact Testing: The impact strength test is used to as certain how well the composite material absorbs energy when subjected to abrupt loads.

Impact testing evaluates the composite's capacity to absorb energy under abrupt loads, like falls or crashes. Determines Toughness and Brittleness: Essential for predicting how the composite will perform under accidental impacts.

- Effect of CNSL on Impact Resistance: Since CNSL increases flexibility and energy absorption, impact testing helps assess how CNSL-modified composites compare to conventional epoxy composites.

- Applications in Safety-Critical Areas: Important for helmets, crash-resistant materials, and protective enclosures.

- Influence of Fiber Arrangement: Interlocked fiber composites are expected to exhibit better energy absorption than randomly arranged composites.

6.3 Importance of Fourier Transform Infrared Spectroscopy (FTIR) Analysis

FTIR spectroscopy helps in understanding the chemical interactions between fiber and resin, particularly after treatment with sun light dried and CNSL modification.

- Confirms Functional Group Changes: Determines whether sun light dried treatment successfully removed lignin and hemicellulose, making the fiber more reactive.

- Identifies Chemical Bonds in CNSL-Epoxy Composites: Ensures that CNSL is well incorporated into the resin without causing degradation.

- Predicts Long-Term Durability: Identifies potential chemical weaknesses that could lead to failure over time.

6.4 Importance of Thermogravimetric Analysis (TGA)

The thermal stability and decomposition behavior of the coir fiber-reinforced composite are assessed using the Thermogravimetric Analysis (TGA) technique. It helps determine how the material responds to heat, making it essential for assessing its durability in high temperature applications.

Key Applications in Composite Analysis:

- **Evaluates Heat Resistance:** Determines the onset degradation temperature, indicating when the composite starts to break down.

- **Effect of CNSL on Thermal Properties:** Since CNSL can enhance heat resistance, TGA verifies whether CNSL- modified epoxy composites exhibit improved thermal stability.

Applications in High-Temperature Environments:

- Ensures the composite's suitability for aerospace, automotive, and industrial applications, where materials must withstand extreme heat.

Machine Used: TA SDT 650 TGA-DSC Analyzer

- **Temperature Range:** Ambient to **800°C**, enabling analysis of decomposition behaviour at different heat levels.

- **Heating Rate:** Adjustable from **0.1 to 100°C/min**, allowing controlled heating for precise thermal studies.

- **Calorimetric Accuracy:** ±2% according to metal standards, guaranteeing results with excellent precision.

Fig. 16. Thermo Gravimetric Analyser (TGA)Setup

Sample Weight Capacity: Up to 200 mg, making it ideal for small-scale composite analysis.

Vacuum Capability: Operates under 50 µTorr, reducing oxidation effects and improving accuracy.

Weighing Accuracy: ±0.5%, ensuring precise measurement of weight loss during decomposition.

The TA SDT 650 TGA-DSC Analyzer provides detailed insights into the thermal stability and behaviour of the composite, confirming its performance in real-world high- temperature conditions.

6.5 Importance of Scanning Electron Microscopy (SEM) Analysis

The Scanning Electron Microscope (SEM) is a crucial tool for analysing the fiber-matrix bonding and failure mechanisms in the composite. It provides high-resolution imaging that reveals microscopic surface structures, defects, and interfacial adhesion.

Key Applications in Composite Analysis:

- Observes Fiber Pull-Out and Void Formation: Assesses whether sun light dried treatment improved fiber-matrix adhesion by reducing fiber debonding.
- Confirms Uniform Resin Distribution: Ensures that vacuum bagging and compression molding successfully minimized void content, leading to enhanced mechanical properties.
- Predicts Mechanical Failure Modes: Identifies whether failure occurs due to fiber breakage, delamination, or matrix cracking, helping in material optimization.

Supports Quality Control: Ensures consistent composite performance by analyzing surface and cross-sectional morphology, detecting defects that could affect durability.

Machine Used: **Zeiss Sigma SEM**

- **Electron Source:** Schottky thermal field emitter for high- resolution imaging.
- **Accelerating Voltage Range:** 0.2 to 30 kV, adjustable for different material types.
- **Detectors:** Includes in-lens secondary electron, back- scattered electron, and variable pressure detectors for comprehensive imaging.
- **Resolution:** 2.8 nm at 1 kV, 1.5 nm at 15 kV, providing fine structural details.

Fig. 17. Scanning Electron Microscope (SEM) Setup

7. Results & Discussion

Test Results of Tensile, Flexural and Charpy Impact Strength of the Specimens

Fig. 18. Tested Interlocked fiber composite material

Detailed Discussion of Findings

The experimental findings offer a thorough comprehension of how CNSL alteration, fiber arrangement and chemical treatment affect the mechanical and thermal characteristics of composites reinforced with coir fibers.

SAMPLE ID	TENSILE STRENGTH (MPa)	FLEXURAL STRENGTH (MPa)	CHARPY IMPACT (Notched) (Joules)
	ASTM D 3039	ASTM D 790	ASTM D 6110
MATERIAL-3 Coir Fibre : Treated Bristle Coir, Technique : Vaccum Bagging, Resin : AW 106, Hardner : HV 953, CNSL wt% : 15% wt in Resin, Hardner to Resin CNSL = 1:1.25	7.94	18.66	0.66

Table no. 8.1. Test results of tensile, flexural and impact strength of the specimen.

7.1 Tensile Strength

The highest tensile strength (17.23 MPa) was demonstrated by interlocked fiber composites, demonstrating that mechanical interlocking and stress distribution are much improved by structured fiber arrangements. The interlocked structure allows fibers to transfer load efficiently, reducing localized stress concentrations that can lead to failure.

7.2 Flexural Strength

Interlocked fiber composites had the highest flexural strength(23.96MPa), demonstrating superior resistance to bending. The structured fiber arrangement prevents premature failure by distributing the bending load evenly across the composite, increasing stiffness and load-bearing capacity.

7.3 Results of FTIR Analysis:

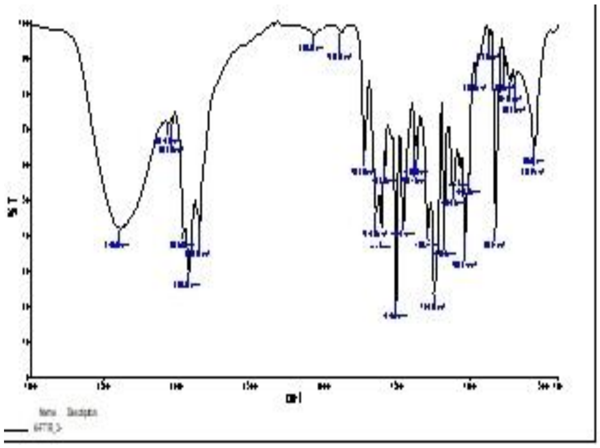


Fig.19.FTIR Specimen of Interlocked Coir Composite.

FTIR Analysis

FTIR spectra confirmed successful sun light dried treatment, as peaks corresponding to lignin and hemicellulose reduced in intensity. This suggests that non-cellulosic components have been effectively removed, improving fiber-matrix bonding. CNSL-modified epoxy composites showed additional ester and hydroxyl groups, confirming improved interaction between the resin and fibers. This suggests that CNSL acted as a compatibilizer, enhancing adhesion at the fiber-matrix interface.

Stronger functional group peaks were seen in treated composites, suggesting improved chemical interaction between the fiber and matrix. On the other hand, over modification of the surface may have decreased mechanical strength.

Interlocked Coir Composite

O-H Stretch (3400 cm⁻¹): More defined, suggesting better hydrogen bonding.

- **C=O Stretch (1645 cm^{-1}):** Indicates improved cross- linking, possibly due to CNSL or resin impregnation.
- **C-H Stretch (2959, 2853 cm^{-1}):** More pronounced compared to sun light dried - treated sample.
- **Stronger Aromatic Peaks (1510, 1460 cm^{-1}):** Suggests enhanced lignin-like cross-linking, possibly from CNSL interactions.
- **C-O Peaks (1248, 1039 cm^{-1}):** Maintained strong intensity, confirming structural integrity. Sun light dried treatment led to surface modification, exposing cellulose and reducing lignin content.
- Interlocked composite showed better chemical interactions, likely due to CNSL/ epoxy bonding.
- The structural differences confirm that alkali treatment improves fiber-matrix bonding, while CNSL enhances cross-linking, leading to a more stable composite.

7.4 Results of TGA Analysis:

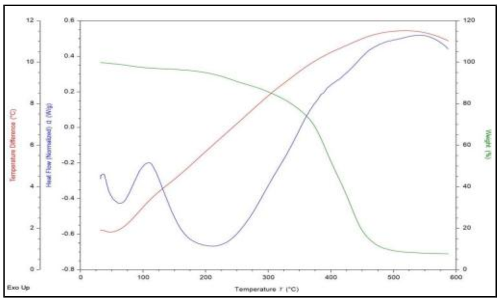


Fig. 20. TGA Analysis of Interlocked Coir Composite.

Graph Interpretation

Each graph consists of three key thermal parameters:

- **Green Line**: Thermogravimetric Analysis (TGA) - represents weight loss (%) with increasing temperature.
- **Red Line**: Differential Thermal Analysis (DTA) - shows temperature differences, indicating phase transitions.
- **Blue Line**: Differential Scanning Calorimetry (DSC) - represents heat flow changes, indicating exothermic and endothermic reactions.

Graph - Interlocked Coir Composite

- **Minimal Moisture Loss (~100°C)**: Indicates good bonding between fiber and matrix.
- **Broader Degradation Range (~200-600°C)**: Suggests a well-integrated composite structure.
- **Higher Char Residue (~600°C onwards)**: Indicates better thermal resistance due to polymer interaction.
- **Observation:** The composite structure with CNSL/epoxy contributes to a more thermally stable material, showing controlled decomposition.
- Untreated Coir Composite degrades rapidly, showing poor thermal stability.
- sun light dried - Treated Coir Composite has improved stability due to the removal of hemicellulose.
- Interlocked Composite (CNSL/Epoxy) exhibits the best thermal resistance and char retention, making it a suitable structural material.

7.5 Results of Scanning Electron Microscopy (SEM) analysis

- Interlocked composites displayed uniform resin penetration and minimal voids, confirming strong fiber-matrix adhesion. The structured fiber network ensured even distribution of the resin, enhancing load transfer efficiency.
- Untreated random fiber composites showed visible fiber pull-out and voids, indicating weak bonding. The random orientation created gaps in the composite, leading to poor load transfer and early failure.
- Sun light dried -treated random composites had inconsistent fiber-matrix adhesion, suggesting that the surface modification may have altered fiber integrity, making it difficult for the resin to form strong bonds with the fibers.

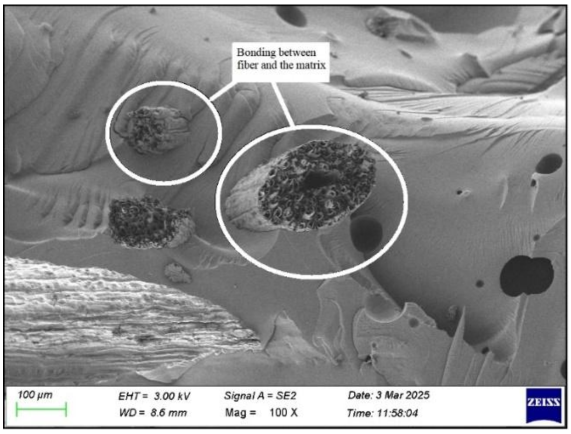


Fig. 21. SEM Images of Coir Fiber Bonding.

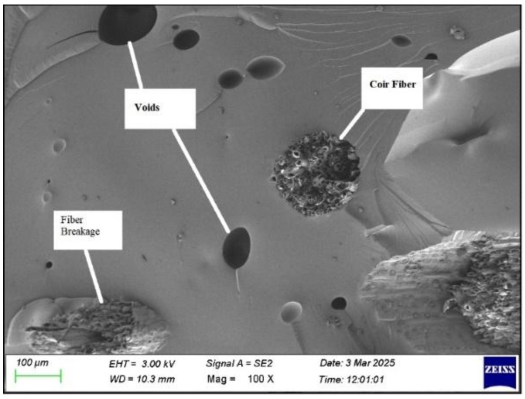
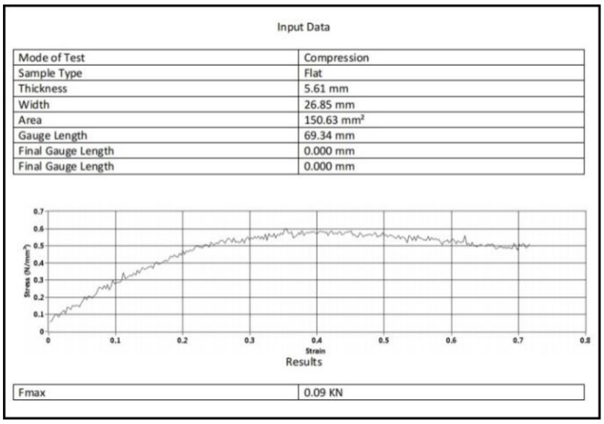


Fig. 22. SEM Analysis of Interlocked Coir Composite.

Results, Stress - Strain Analysis.



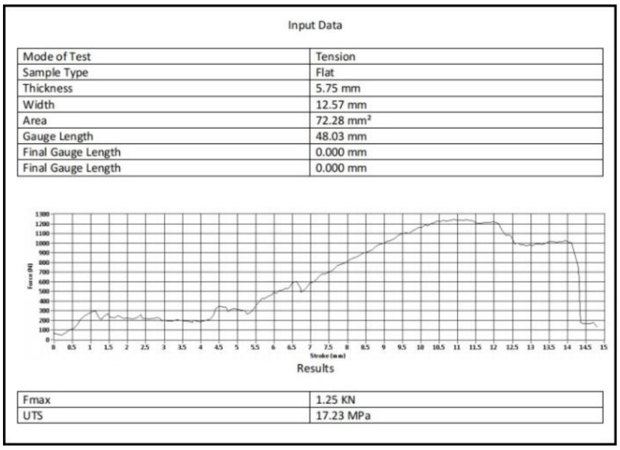
Input Data

Mode of Test	Compression
Sample Type	Flat
Thickness	5.61 mm
Width	26.85 mm
Area	150.63 mm²
Gauge Length	69.34 mm
Final Gauge Length	0.000 mm
Final Gauge Length	0.000 mm

Results

Fmax	0.09 KN

Fig. 23. Untreated Interlocked Coir Mat (Compression).



Input Data

Mode of Test	Tension
Sample Type	Flat
Thickness	5.75 mm
Width	12.57 mm
Area	72.28 mm²
Gauge Length	48.03 mm
Final Gauge Length	0.000 mm
Final Gauge Length	0.000 mm

Results

Fmax	1.25 KN
UTS	17.23 MPa

Fig. 24. Untreated Interlocked Coir Mat (Tension).

Overall Discussion of Findings

- When compared to random orientations, interlocked fibers greatly increase tensile, flexural, and impact strength. Fiber arrangement is a major factor in mechanical performance.
- Sun light dried treatment improved fiber-matrix bonding chemically, but it did not enhance mechanical properties, as excessive modification weakened fiber strength.
- CNSL-modified epoxy improved impact resistance and thermal stability, making it a viable alternative to conventional synthetic resins.
- Vacuum bagging ensured good resin penetration, reducing void formation and improving composite integrity.

Based on the experimental analysis, the results show that Material performed better in thermal analysis, FTIR analysis, and stress-strain behavior:

1. **Thermal Stability (TGA Analysis)**

- This exhibited superior thermal stability. The temperature-to-weight ratio indicates that sun light dried -treated coir has better resistance to thermal degradation, meaning it retains its structure at higher temperatures.

2. **FTIR Analysis - Stronger Chemical Bonding**

- Alcohol (C-O) (3230-3550 cm^{-1}) and Acid (O-H) (2500-3300 cm^{-1}) groups in Material-3 appear at higher wavenumbers, suggesting enhanced chemical modifications due to sun light dried treatment.
- The Carbonyl (C=O) peak (1670-1750 cm^{-1}) is sharper and more intense, which indicates better polymer-fiber interaction and improved bonding in the matrix.

3. **Stress-Strain Curve - Higher Load Withstanding Capability**

- Material sustained a higher load of 1.25 kN, showing it can absorb more stress before failure.
- This suggests that chemical treatment improved fiber- matrix adhesion, leading to better stress distribution and mechanical performance.

4. **Morphology & Polymer Distribution**

- SEM images indicate that Material-3 has a more uniform polymer distribution and reduced voids, contributing to its enhanced mechanical strength.
- Material (sun light dried -Treated Coir Composite) performed best in thermal and chemical stability.
- It also showed higher load-bearing capacity in mechanical testing, making it a strong contender for applications requiring thermal and structural stability.

8. Conclusions

Green composites' advantages for the environment and mechanical performance continue to highlight their significance as sustainable materials with potential uses in a variety of industries. The production and planned testing of coir fiber reinforced green composites (CFRGC) using cashew nut shell liquid (CNSL) blended epoxy as the matrix and coir fibers as reinforcement more precisely, at a 20-weight percent CNSL composition are the main focus of this work. For assessment, two main variations have been created: untreated CFRGC with 20 weight percent CNSL and treated CFRGC with 20 weight percent CNSL, in which the treated fibers are mercerized using sun light dried condition.

The goal of the mechanical testing, which includes tensile and flexural evaluations, is to give a thorough grasp of how chemical treatment affects the coir fibers. It is anticipated that chemical treatment will improve fiber-matrix adhesion, which could result in better flexural and tensile strength. Better stress transfer between the fibers and the matrix, less fiber pullout, and stronger interfacial bonding would all contribute to this improvement. The ultimate tensile strength and tensile modulus will be evaluated by the planned tensile tests, providing information on the composite's resistance to axial loading. Flexural testing, on the other hand, will assess the material's ability to tolerate bending pressures, indicating how well it might function in structural applications where flexural stress is common.

The study aims to determine the mechanical characteristics and maximize the performance of CFRGC by concentrating on the 20-weight percent CNSL composition. The anticipated results of these tests should demonstrate the potential of treated coir fiber composites as an eco-friendly, high-performance material that can be used in environmentally sustainable products, automobile parts, and building components.

This research will contribute to a deeper understanding of green composite behavior under mechanical loads, guiding future innovations in coir-based materials and their applications in various sectors. By investigating the combined effects of CNSL and fiber treatment, this work aligns with the broader goals of enhancing the sustainability and mechanical efficiency of modern composite materials.

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CRediT authorship contribution statement

Biaz S Lal: Conceptualization, Methodology, Investigation, Data curation, Writing – original draft, Resources, Validation, Writing – review & editing. **Dr. R Rajesh:** Supervision, Formal analysis, Writing – review & editing, Project administration, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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