

Research Article

Mechanical and Thermal Characterization of Natural Composites for Sustainable Applications

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Abstract:

This study explores the development and mechanical characterization of sustainable hybrid composites reinforced with rockwool, conch shell powder, and flax fibers within an epoxy matrix. Two distinct composite formulations were fabricated: Rockwool/Conch/Epoxy (C-1) and Rockwool/Flax/Epoxy (C-2), each comprising 30 wt.% reinforcement (15 wt.% rockwool fibers and 15 wt.% conch powder or flax fibers) and 70 wt.% epoxy resin. The composites were produced using the hand lay-up method followed by compression molding. Comprehensive mechanical tests, including tensile and flexural strength assessments, were conducted in accordance with ASTM standards. Additionally, thermogravimetric analysis (TGA), water-absorption testing and scanning electron microscopy (SEM) were employed to evaluate thermal stability, moisture affinity, and microstructural characteristics. The results indicated that C-2 exhibited superior tensile and flexural strengths compared to C-1, attributed to the enhanced fiber-matrix bonding facilitated by flax fibers. Conversely, C-1 demonstrated better thermal stability but also higher water uptake, reflecting the porous, hydrophilic nature of conch shell particles. SEM analysis revealed effective dispersion of reinforcements and strong interfacial adhesion in C-2, whereas C-1 showed minor voids around conch particles. These findings highlight the potential of integrating natural and industrial waste materials to develop high-performance, eco-friendly composites with tailored mechanical, thermal, and moisture-management properties suitable for various structural applications.

Keywords: Natural Fiber, Composite, Rockwool, Conch Shell, Flax, Epoxy, Mechanical Characterization

1. Introduction

Natural fiber composites have garnered significant attention in recent years due to their environmental benefits and sustainable properties. Among these, rockwool, derived from volcanic rocks and other mineral-based sources, has emerged as a promising reinforcement material in polymer composites. As a natural fiber, rockwool offers high thermal resistance, sound absorption, and lightweight characteristics, making it suitable for a wide range of applications, including construction, automotive, and aerospace industries. In the last decades, Glass wool Fibers (GWFs) and Rock wool Fibers (RWFs) are widely used as insulator materials because of their eligible thermal properties, light weight, high tensile strength, and low cost [1, 2].

Crushed conch shell particles have recently been adopted in composite fabrication, leveraging their ecological benignity and longstanding use in decorative arts. In this study, conch shell powder (sieved to $\leq 600 \mu\text{m}$) was incorporated into E-glass fiber/epoxy composites at weight fractions of 25 %, 35 %, 45 % and 55 % using the hand

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lay-up method [3]. Flax, known scientifically as *Linum Usitatissimum*, is an annual plant whose stems and seeds are used to produce fiber. The plant can grow to heights of 0.6–1.2 m, with stem diameters ranging from 1 to 3 mm. Flax fiber is highly prized due to its superior quality and yield compared to other available fibers [4]. Among vegetable fibers, flax is the most promising thanks to the highest specific tensile modulus and strength [5]. To achieve sound absorption across a broad range of frequencies, composite structures made from various sound-absorbing materials are necessary, as no single material can efficiently cover all frequency ranges [6]. Porous materials can be further classified into synthetic (organic and inorganic) and natural fibers. Although synthetic fibers have been widely used as conventional sound-absorbing materials, their environmental impact is a significant drawback. The growing global demand for eco-friendly products has driven the exploration of natural fiber-reinforced composites (NFRCs) for acoustic applications, which offer similar acoustic properties to synthetic materials but with a much lower environmental footprint [7]. These natural materials are biodegradable and renewable, providing important advantages such as optimal mechanical, thermal, and acoustic properties, recyclability, and renewability. Additionally, natural fibers have lower carbon footprints, reduced energy consumption during production, and offer greater availability, low cost, low density, and no allergy issues, making them viable alternatives to synthetic fibers for polymer composite reinforcements [8–16]. However, despite their advantages, natural fiber composites face challenges, such as high moisture content, low flame resistance, weak surface adhesion, vulnerability to microbial attack, and the need for specific processing temperatures [17].

The development of high-performance materials derived from natural resources is gaining traction worldwide due to their abundant availability, cost-effectiveness, lightweight nature, and superior specific modulus compared to synthetic fibers [18, 19]. Additionally, these materials are biodegradable, renewable, and exhibit a lower specific weight alongside higher specific strength and stiffness compared to glass fibers. Their advantages also include ease of processing, reduced wear, and excellent thermal and acoustic insulating properties [20–22].

Among these natural fibers, hemp fiber has recently attracted significant attention for its diverse applications as a reinforcing agent in the composite industry, as well as in housing, railways, and aerospace sectors. This is due to its exceptional mechanical properties, such as high specific strength and stiffness, as well as its impressive Young's modulus [23, 24]. However, a major limitation of natural fibers as reinforcements is the poor interfacial adhesion between the hydrophilic, polar natural fibers and hydrophobic, non-polar polymers. To address this issue, various coupling agents have been employed to improve the compatibility between natural fibers and thermoplastic matrices, thereby enhancing the overall performance of the composites [25,26].

The primary objective of this research is to develop epoxy-based hybrid composites reinforced with rockwool, conch shell powder, and flax fibers and evaluate their mechanical and thermal properties. Two distinct composites, Rockwool/Conch/Epoxy (C-1) and Rockwool/Flax/Epoxy (C-2), were fabricated using the hand lay-up method followed by compression molding. The study assesses tensile and flexural strengths, evaluates thermal stability using TGA, water absorption test and examines microstructural features with SEM to analyze reinforcement dispersion and fiber-matrix adhesion. It compares the performance of C-1 and C-2 to determine the influence of reinforcement types and highlights the sustainability benefits of using natural and waste materials in composites.

2. Materials and methods

The methodology for this research involves the fabrication and characterization of two hybrid epoxy-based composites: Rockwool/Conch/Epoxy (C-1) and Rockwool/Flax/Epoxy (C-2). The process is outlined and clarified below for reproducibility and precision:

2.1 Materials Preparation

The materials used in this research were carefully selected to ensure the successful fabrication and characterization of Rockwool/Conch Powder/Epoxy and Rockwool/Flax Fiber/Epoxy reinforced composites. Rockwool fibers, derived from basalt rocks, were chosen as the primary reinforcement material due to their high thermal resistance, good mechanical properties, and compatibility with polymer matrices. Conch powder, a natural filler rich in calcium carbonate (CaCO_3), was incorporated to enhance the stiffness and thermal stability of the composite. Additionally, flax fibers, known for their high tensile strength and flexibility, were included to complement the rigidity of Rockwool and balance the composite's mechanical performance.

Rockwool was selected as the natural fiber for the composites due to its insulating properties. The density of Rockwool used in this study is 120 kg/m³ [27]. Conch powder, an inorganic powder, was used as a reinforcement along with Rockwool in one of the composite formulations. The density of the Conch powder is assumed to be 2800 kg/m³ [30]. Flax fiber, known for its strength and eco-friendliness, was used in combination with Rockwool for another composite formulation. The density of Flax fiber is 1400 kg/m³ [29]. Epoxy resin (1200 kg/m³) [28] was chosen as the matrix for the composites due to its strong bonding characteristics. The resin was mixed with the hardener (HY951) in a 3:1 weight ratio.

2.2 Treatment of Materials

Rockwool fibers were cut into uniform lengths of 50 mm to ensure consistency in reinforcement distribution. No additional surface treatment was applied to these fibers. Conch shells were cleaned, dried, and ground into fine powder, achieving a particle size distribution of 15–30 μm. The powder was sieved to ensure uniformity. Flax fibers were treated with a 5% NaOH solution for 4 hours to remove surface impurities, waxes, and lignin. This treatment enhances interfacial bonding with the epoxy matrix. The fibers were then rinsed with distilled water, neutralized with 1% acetic acid, and dried in an oven at 60°C for 24 hours.

2.3 Fabrication of Composite

The composites were fabricated using the hand lay-up method followed by compression molding. The Rockwool fibers were cut into lengths of 50 mm, and the conch powder and flax fibers were prepared accordingly. The epoxy resin and hardener mixture were prepared in a 3:1 weight ratio to achieve a uniform consistency. The acrylic mold (200 × 200 × 6 mm³) was cleaned and coated with a mold-release wax to facilitate easy removal of the composite after curing. The reinforcements, including Rockwool fibers, conch powder, and flax fibers, were carefully weighed and layered into the mold to maintain uniform distribution and alignment. The resin-hardener mixture was poured over each layer to ensure proper wetting of the reinforcements. Once all layers were assembled, the mold was closed, and a uniform pressure of 5 MPa was applied using a hydraulic press to compact the composite and eliminate air voids. The composite was allowed to cure at room temperature for 24 hours, followed by post-curing in an oven at 80°C for three hours to improve mechanical and thermal properties. The cured composite sheets were then cut into specimens along the same principal direction of reinforcement alignment to ensure consistency of standard dimensions for mechanical characterization, including tensile (ASTM D638) and flexural (ASTM D790) tests, thermal analysis using TGA, and microstructural analysis through SEM. This process ensured the development of high-quality hybrid composites with precise mechanical and thermal properties.

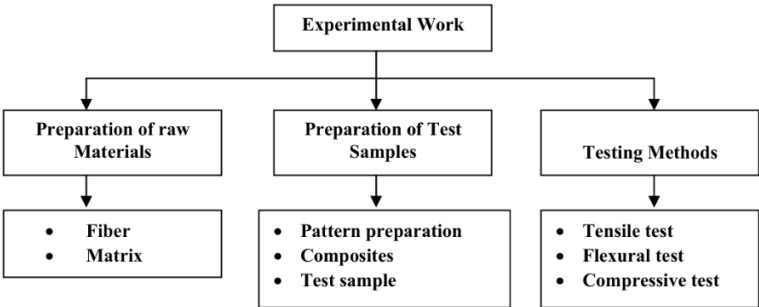


Fig. 1. Flowchart detailing each step of the methodology

Table 1: Composite sample with details

Sample	Details	Code
Rockwool/Conch/Epoxy	30 wt. % of (15% each) of Rockwool fiber sheet and Conch powder + 70 wt. % of epoxy	C-1
Rockwool/ Flax/Epoxy	30 wt. % of (15% each) of Rockwool fiber sheet and flax fiber + 70 wt. % of epoxy	C-2

A 30 wt.% total filler content was selected for both formulations based on early optimization studies. Below 25 wt.% reinforcement, stiffness improvements were marginal, while loadings above 35 wt.% led to mixing difficulties, poor

wetting and increased porosity. At 30 wt.% (15 wt.% rockwool + 15 wt.% conch shell for C-1; 15 wt.% rockwool + 15 wt.% flax for C-2), we achieved an optimal compromise between mechanical performance and manufacturability.

3. Results and discussion

3.1 Characterization

The mechanical and thermal properties of the fabricated C-1 and C-2 composites were evaluated using standardized testing techniques. The characterization focused on tensile strength, flexural strength, thermogravimetric analysis (TGA), and scanning electron microscopy (SEM) to understand the composites' mechanical behavior, thermal stability, and microstructural features.

3.1.1 Tensile Strength Analysis

The tensile strength of the composites was measured according to ASTM D638 standards as shown in Figure 2(a)(b). The specimens were prepared with dimensions of $165 \times 15 \times 6$ mm³, ensuring adherence to testing protocols. Tensile tests were performed using a universal testing machine (UTM). In Figure 2(c), stress (vertical axis) rises with strain (horizontal axis) in two distinct ways for C-1 and C-2, first both curves start nearly straight—small increases in strain produce proportional increases in stress. The C-2 curve climbs more sharply, so at, say, 10 MPa stress C-2 only needs about 1 % strain, whereas C-1 needs roughly 1.3 % strain. Then second, C-2 reaches its maximum stress (approx. 17 MPa) at around 2.6 % strain and then drops off abruptly, indicating rapid fracture once its load-bearing limit is exceeded. By contrast, C-1 continues loading up to a higher stress (approx. 30 MPa) at about 4.8 % strain and then shows a more gradual post-peak decline, meaning it can absorb more deformation before breaking. Thus, C-2 gains stress more quickly with strain but fails at a lower strain, while C-1 can withstand larger deformations and higher peak stress before fracture. The tensile properties were analyzed to assess the load-bearing capacity of the composites, with comparisons drawn between the two types of reinforcements.

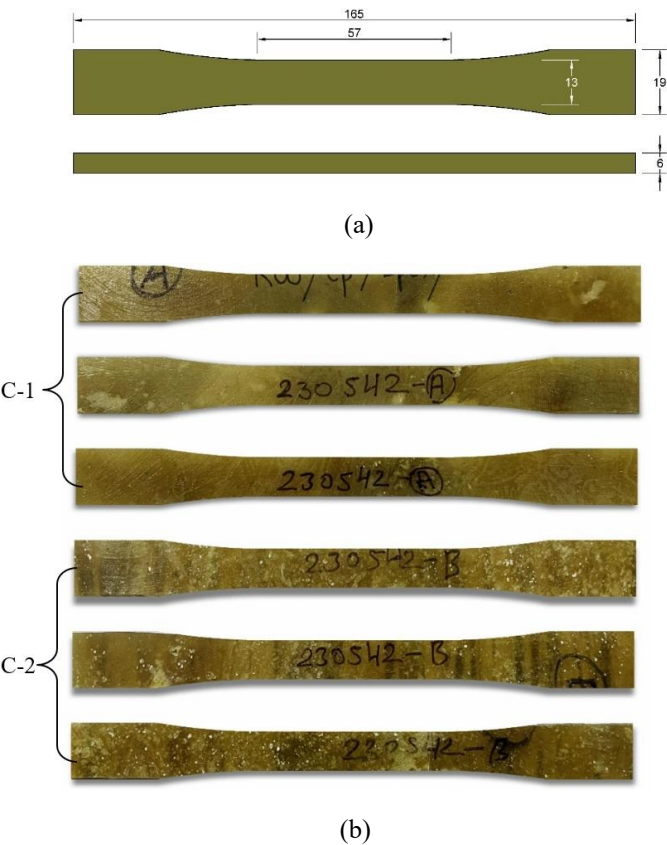


Fig. 2. (a). Line diagram of the Tensile test specimen (b). Test specimen (C-1 and C-2)

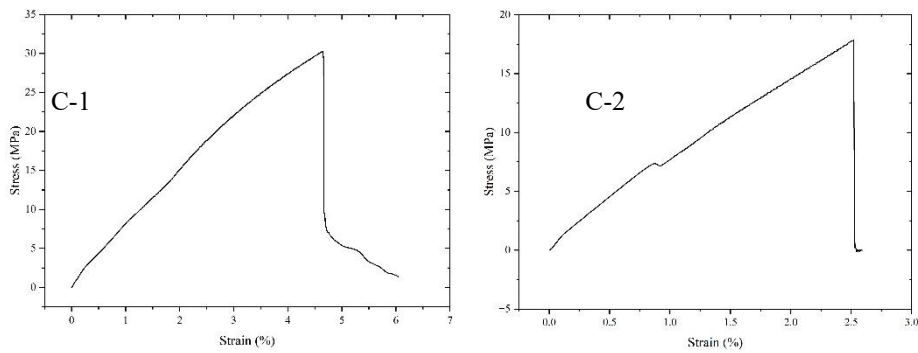


Fig. 2. (c). Stress-strain curve of composites (C-1 and C-2)

Table 2 shows that C-2 (809 MPa) is stiffer than C-1 (725 MPa), meaning it resists deformation more strongly at low strains. However, C-1 endures greater deformation before breaking (4.78 %) compared to C-2 (3.44 %), indicating higher ductility. The larger variability in C-1's modulus (± 141 MPa vs. ± 31 MPa) suggests its filler dispersion is less uniform.

Table 2: Values of Young's Modulus and Elongation at Break

Sample	Young's Modulus (MPa)	Elongation at Break (%)
C-1	725 ± 141	4.78 ± 0.20
C-2	809 ± 31	3.44 ± 0.75

3.1.2 Flexural Strength Analysis

Flexural strength testing was conducted following ASTM D790 standards (as shown in Figure 3) to evaluate the bending performance of the composites. Specimens of dimensions $155 \times 13 \times 6$ mm³ were tested using a three-point bending setup on a UTM. A span-to-depth ratio of 16:1 was maintained, and the test was carried out at a constant strain rate. The flexural strength and modulus were calculated based on the load-displacement data. The results highlighted the influence of fiber type and sequence on the composites' bending behavior.

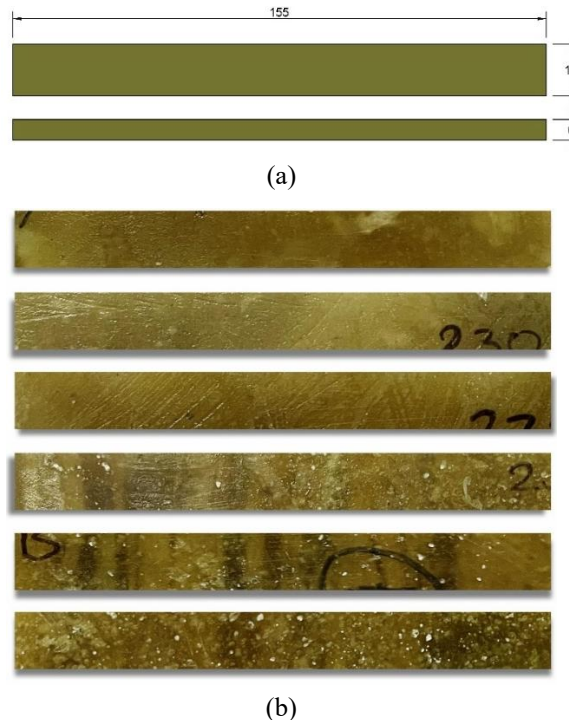


Fig. 3. Flexural test specimen; (a) Line diagram, (b) Test specimen (C-1 and C-2)

3.1.3 Thermogravimetric Analysis (TGA)

Thermal stability and decomposition behavior of the composites were studied using TGA. TGA was performed in a nitrogen atmosphere from room temperature to 800°C at a heating rate of 10°C/min. The weight loss versus temperature curves were analyzed to determine the thermal degradation stages of the composites. Key parameters such as the onset decomposition temperature, peak decomposition temperature, and residual mass at high temperatures were recorded. TGA results provided insights into the influence of fiber and matrix on the thermal stability of the composites.

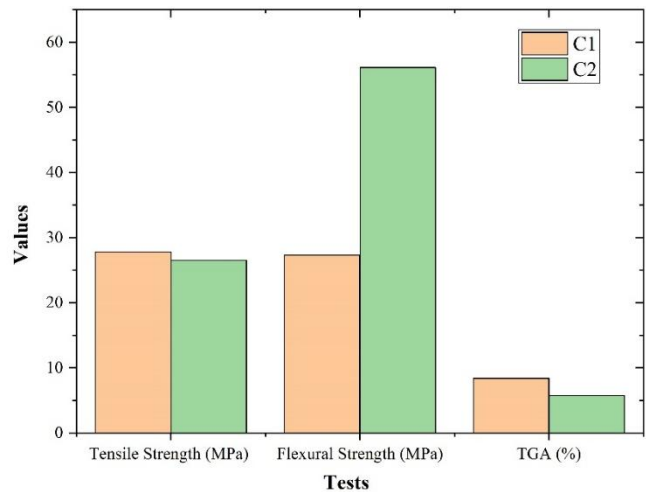


Fig. 4. Flexural test specimen; (a) Line diagram, (b) Test specimen (C-1 and C-2)

The Figure 4 compares the mechanical and thermal properties of two composite types: C-1 and C-2. The properties evaluated include tensile strength (in MPa), flexural strength (in MPa), and thermal degradation (TGA in percentage). For tensile strength, both composites exhibit comparable values, reflecting their similar ability to withstand tensile loading. However, there is a slight variation, with C-1 showing marginally higher tensile strength than C-2. This suggests that the addition of Conch powder in C-1 contributes to reinforcing the matrix, providing better load distribution during tensile loading.

The flexural strength shows a more significant difference between the two composites. C-2 demonstrates considerably higher flexural strength compared to C-1. The inclusion of flax fibers in C-2 enhances its resistance to bending forces, likely due to the superior bonding and load transfer efficiency between the flax fibers and the epoxy matrix. In contrast, the Conch powder in C-1 may not provide sufficient reinforcement under flexural loads, leading to lower performance in this aspect. In terms of thermal stability, measured by TGA (Thermogravimetric Analysis), both composites show relatively low values, but C-2 exhibits slightly higher thermal degradation resistance compared to C-1. This indicates that the flax fibers in C-2 contribute more effectively to maintaining structural integrity at elevated temperatures, compared to the Conch powder in C-1.

The Figure 5 represents the thermogravimetric analysis (TGA) results of two composite materials: C-1 and C-2. It shows the weight loss (%) of the composites as a function of temperature (°C) during thermal degradation, illustrating their thermal stability. Initially, both composites exhibit a gradual weight loss as temperature increases from 30°C to around 300°C. This phase corresponds to the evaporation of moisture and the release of low-molecular-weight volatiles. C-1 shows a slightly higher weight loss in this region compared to C-2, indicating that the presence of Conch powder in C-1 may introduce additional volatile components. Between 300°C and 600°C, a significant weight loss is observed for both composites, marking the primary degradation of the polymer matrix and the breakdown of organic components such as epoxy resin and natural fibers. C-2 demonstrates better thermal stability in this range, as indicated by its slightly lower rate of weight loss compared to C-1. This enhanced stability can be attributed to the flax fibers in C-2, which have superior thermal resistance compared to the Conch powder in C-1. Beyond 600°C, the weight stabilizes for both composites, leaving residual ash content. The ash content, indicated as 8.39% for C-1 and

5.75% for C-2, suggests that C-1 retains more inorganic residue, likely due to the mineral content in the Conch powder. In contrast, C-2 exhibits lower residual ash, consistent with its organic fiber reinforcement.

Overall, the graphs highlight the distinct performance of the two composites, where C-1 performs better in tensile strength, while C-2 excels in flexural strength and thermal stability. These differences underline the influence of the reinforcement type Conch powder or flax fiber on the mechanical and thermal behavior of the composites. Also, that C-2 offers slightly better thermal stability, with a higher delta weight loss (94.247%) compared to C-1 (91.611%), making it more suitable for applications requiring resistance to higher temperatures.

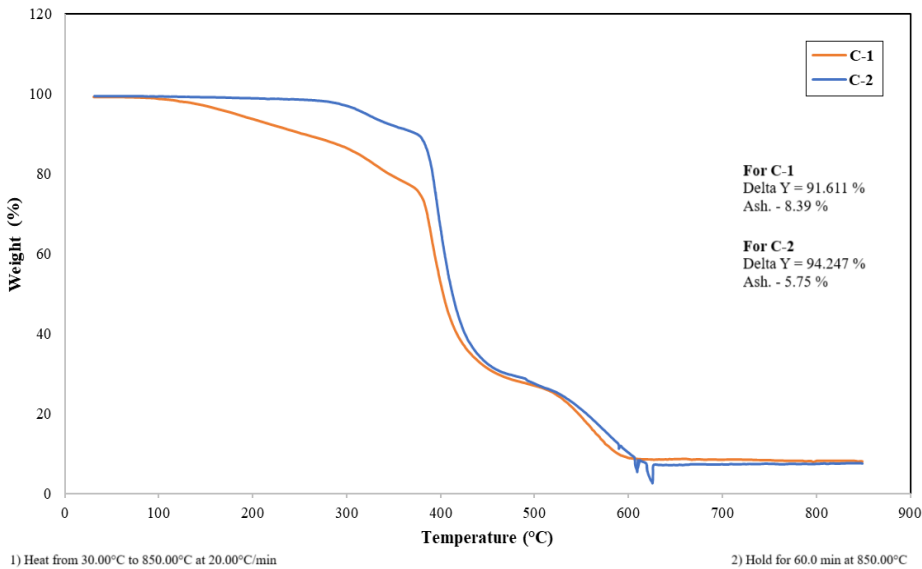


Fig. 5. TGA weight-loss curves for C1 and C2 composites, annotated to indicate (i) moisture/volatile loss (30–200 °C), (ii) hemicellulose/cellulose decomposition (200–350 °C), and (iii) epoxy backbone degradation (350–600 °C)

3.1.4 Water Absorption Test

Water uptake was measured per ASTM D570 by immersing specimens in deionized water at 23 °C for 24 h. After blotting away surface water, samples were weighed to determine percent uptake. As shown in Table 3, C-1 exhibits higher uptake (3.77 wt.%) due to the porous morphology and hydrophilic surface of conch-shell particles, which facilitate water ingress. By contrast, C-2 absorbs less water (2.47 wt.%) because the flax–epoxy interface and the smoother surface of rockwool fibers limit moisture penetration. These differences in water affinity influence the composites’ physicochemical behavior: higher water uptake in C-1 can lead to greater matrix plasticization and reduced stiffness under humid conditions, whereas C-2’s lower uptake suggests improved dimensional and mechanical stability in moisture-rich environments.

Table 3: Water absorption behavior of hybrid composites

Sample	Water Uptake (wt.%)
C1	3.77
C2	2.47

3.1.5 Scanning Electron Microscopy (SEM) Analysis

The surface morphology and fracture behavior of the composites were analyzed using SEM. Samples from the tensile and flexural tests were observed to investigate the fiber–matrix adhesion, fiber pull-out, and void content. The SEM images revealed details about the dispersion of Rockwool, conch powder, and flax fibers within the epoxy matrix. Additionally, microstructural defects such as voids and cracks were examined to correlate the microstructure with the observed mechanical properties.

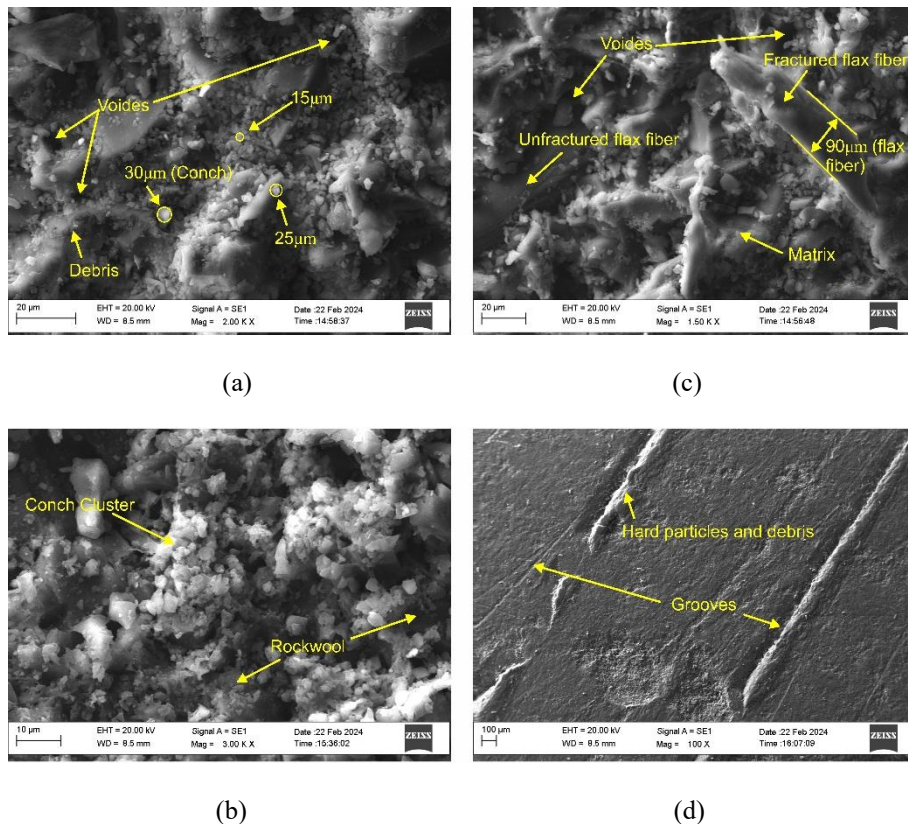


Fig. 6. SEM image of composite material C-1 & C-2; (a) Conch-shell particles in epoxy; (b) Rockwool fiber clusters; (c) Flax-fiber pull-out features; (d) Wear grooves and debris

The SEM images provide a detailed visualization of the microstructural characteristics of the two composite types, C-2 and C-1 as shown in Figure 6. In this Figure (Figure 6 (a)) highlights conch powder particles of various sizes (15–30 μm) dispersed in the epoxy matrix. The voids and debris around the particles suggest potential areas of weak bonding or interfacial detachment between the matrix and the conch powder. These features can affect the overall mechanical and thermal properties of the composite. However, the conch's granular structure indicates a possible contribution to improved thermal stability. This high-magnification image (Figure 6 (b)) illustrates clusters of conch particles and rockwool fibers within the matrix. The presence of conch clusters suggests agglomeration during mixing, potentially reducing uniform stress distribution. Rockwool fibers appear dispersed, contributing to mechanical reinforcement. However, voids around these particles indicate potential weak zones.

The microstructure reveals (Figure 6 (c)) the presence of fractured and unfractured flax fibers embedded within the epoxy matrix. The fractured flax fibers suggest fiber breakage under mechanical stress, contributing to energy absorption during tensile loading. Voids are also visible, indicating possible manufacturing defects or inadequate fiber-matrix adhesion, which can reduce mechanical performance. The unfractured fibers suggest partial fiber-matrix bonding, indicating that certain regions remain intact during mechanical loading. This Figure 6 (d) shows grooves and hard particles, likely due to surface abrasion or mechanical testing. The grooves indicate localized wear patterns, while the debris suggests material removal under stress. These features provide insight into the composite's wear and frictional behavior.

4. Conclusion

The research successfully developed and characterized two hybrid epoxy-based composites reinforced with rockwool, conch shell powder, and flax fibers. The Rockwool/Flax/Epoxy composite (C-2) demonstrated superior tensile and flexural strengths compared to Rockwool/Conch/Epoxy (C-1), thanks to the stronger fiber–matrix bonding of flax fibers which promotes efficient stress transfer. Conversely, C-1 exhibited greater thermal stability but also higher

water uptake (3.77 wt. % vs. 2.47 wt. % for C-2), reflecting the porous nature of conch shell powder. SEM analysis confirmed these trends, showing well-dispersed flax fibers and clean interfaces in C-2, and minor voids around conch particles in C-1. By combining natural and industrial waste fillers, these composites achieve a balance of mechanical, thermal, and moisture-management properties while advancing sustainability. Future work will optimize filler dispersion, investigate surface treatments to further enhance interfacial adhesion, and evaluate long-term performance under environmental exposure for broader industrial applications.

Data Availability

The data required to reproduce these findings are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

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