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Research Article

Enhancement of Mechanical Properties of Coir, Kapok, and Hemp Fiber-Reinforced Epoxy Composites for a Variety of Applications

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ABSTRACT

Natural fiber composites (NFC), as the name implies, are created from natural resources and so have environmental benefits such as biodegradability. NFC has grown in popularity in recent years due to its natural properties in a wide range of applications, including automotive, commodities, structural, and infrastructure. The aim of this research is to use ineffective natural fibers to create effective societal applications. This work uses coir as a foundation material and hemp and kapok as fibers/filler materials. The weight proportion of coir was held constant, while the remaining two fibers/fillers were changed. To observe mechanical parameters, ductile, flexural, impact, and hardness tests were performed in line with ASTM regulations. The experimental results show that sample D (25% coir, 20% hemp, 5% kapok) demonstrated the highest mechanical performance, with a tensile strength of 66.28 MPa, flexural strength of 138.92 MPa, impact strength of 9 J/m^2, and hardness of 74.18 Shore D. Scanning electron microscopy (SEM) examinations of composite fracture surfaces revealed that fiber surface alteration occurred, improving fiber-matrix adhesion. These composites can be used for a wide range of industrial, commercial, and consumer-based advancements.

1. Introduction

Natural fibers are classed according to their origin, chemical composition, and structure. Cotton, jute, bamboo, hemp, sisal, flax, ramie, and coconut coir are among the most common plant fibers [1, 2]. These fibers are largely composed of cellulose, which is a polysaccharide found in plant cell walls. Animal fibers generated from animals or insects include silk, wool, hair, and down. While some fibers, such as flax and cotton, are predominantly cellulose-based, others, such as silk and wool, are protein-based and contain keratin. Furthermore, some plant fibers, such as hemp and jute, contain lignin, which enhances structural integrity. Natural fibers have demonstrated considerable potential for developing composite materials since they are renewable, cost-effective, environmentally beneficial, and carbon-neutral [3, 4]. Mwaikambo and Ansell [5] examined the effects of alkalizing hemp, sisal, jute, and kapok fibers. The findings indicate that alkalization changes

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plant fibers, increasing the establishment of fiber-resin adhesion, which leads to higher interfacial energy and, as a result, improved mechanical and thermal stability of the composites. Oladele et al. [6] investigated the effects of alkaline-modified coir and unmodified hemp fiber reinforced epoxy composite. According to the results, the sample with 5 wt.% coir exhibited the best property combination in terms of tensile attributes such as tensile strength, tensile modulus, flexural strength, and impact strength. Kassim et al. [7] studied the effect of coir fiber and kapok on layer structure samples. They obtained the results using a mixture of coir fibers with varying layer thicknesses, and the inclusion of a 2 mm thick kapok layer results in a significant improvement in absorption bandwidth. The kapok fiber layer put between the coir fiber layers also improves the absorption frequency bandwidth the most. Sarıkaya and Susurluk [8] investigated the impact of polypropylene, kapok, and coir additives on the mechanical and thermal parameters of concrete samples. From the outcomes, the workability of fiber-added concrete is low; the mechanical properties of fiber-added concrete gain more importance, especially in the challenging geographical and environmental conditions. Increasing fiber dosage in fluid concrete brings about a decrease in slump. Based on the literature outcomes, no research investigations have been conducted on the effects of three diverse natural fibers (coir, hemp, and kapok) on composite materials. This study was the first to assess the mechanical properties of coir, hemp, and kapok reinforced epoxy matrices. However, this study looked into the intricate interactions between the mechanical properties of natural fiber hybrid composites, such as flexural, ductile, impact, and hardness. Furthermore, the SEM morphological images show the interaction among the fibers and matrix.

2. Materials and Methodology

The selection of appropriate materials is an essential part of any composite fabrication process. The major elements for this investigation were three natural fibers, such as coir, hemp, and kapok, as shown in Fig. 1, and the mechanical attributes are represented in Table 1. Araldite epoxy resin and hardener are also utilized as binding materials, which may be purchased at Ram Hardware in Hyderabad, India. Coir was sourced from a local coconut trader, hemp from India Mart, and kapok from Pochampally village in Hyderabad, India.

The epoxy system in the sample consists of 70% clear epoxy resin and 30% hardener. Clear epoxy resin's viscosity ranges from 11,000 to 14,000 cps.

Fig. 1. Natural fibers selected for this work: a. Coir, b. Hemp, and c. Kapok

Table 1. Mechanical attributes of selected fibers [8]

Properties	Coir	Hemp	Kapok
Density (g/cm^3)	1.15-1.50	1.4-1.5	0.04-0.09
Tensile strength (MPa)	100-250	250-1100	70-100
Young's modulus (GPa)	4-6	30-70	1.5-4
Elongation at break (%)	15-40	1.6-4	1-3
Moisture absorption (%)	8-10	8-12	3-5

2.1. Alkaline Treatment

A process for preparing alkaline for treatment is shown in Fig. 2. The fibers of kapok, hemp, and coir were alkalized at a regulated room temperature of up to 28°C using a sodium chloride solution. The composites were immersed in the alkali solution for two hours, cleaned with filtered water, and then rinsed with tap water several times [9]. They were then dried in the oven for a full day at a particular temperature of 100°C to remove any remaining moisture. This stage entails removing moisture from the fibers after they have been washed and neutralized to obtain a stable and durable state. The fibers are then dried in a controlled atmosphere to ensure consistency and avoid damage.

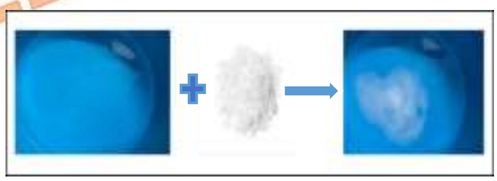
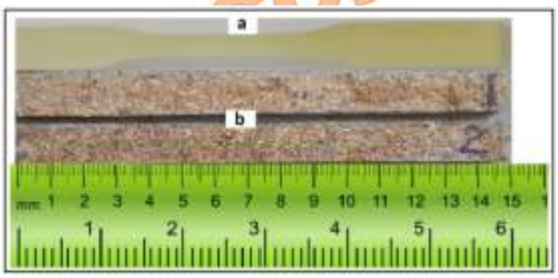


Fig. 2. Alkaline treatment process

2.2. Preparation of Composite Samples

A mill board mould of 150 mm × 75 mm and 4 mm in thickness, including a hollow interior, is necessary for the hand lay-up of natural fiber-reinforced composites. The hollow interior facilitates the uniform placement and consolidation of composite layers composed of fibers and resin. This study uses the hand layup technique to make composite samples. Oil is applied to the mould surface to inhibit fiber adhesion. Thin aluminum foil sheets are positioned on the upper and bottom surfaces of the mould plate to ensure the product possesses a flat surface. Subsequently, liquid epoxy is meticulously combined (10:1) with a specified hardener and applied to the surface of the mould. The epoxy is applied uniformly using a brush. Subsequent to the application of a second layer of alkali-treated natural fibers, including coir, hemp, and kapok, onto the epoxy surface with diverse compositions, a roller is employed to traverse the fibers and epoxy layer while exerting gentle pressure to expel any entrapped air and surplus epoxy. The process is repeated for each layer of epoxy and fibers until the samples attain the requisite dimensions. Once the mould is opened and allowed to cure for 24 hours at ambient temperature, the final composite sample is extracted and subjected to additional processing. Depending on the materials used and the desired properties, heat, pressure, or a combination of the two may be required during the curing process. Because of their roughened surfaces and fewer impurities, the alkali-treated fibers utilized in this study permit better bonding during curing, hence increasing the composite's overall performance. Table 2 depicts the weight ratio of resin and fiber. Figures 3 and 4 demonstrate the fabrication process for composites and fabricated samples, respectively.

(a) Coir, (b) Hemp, (c) Kapok selection of fibers,
(a1) Coir, (b2) Hemp, (c3) Kapok fibers immersed in alkaline solution, (d) Mould, (e) Fabricated composite
Fig. 3. Fabrication process of composite samples



a) Epoxy sample and b) composite samples
Fig. 4. Fabricated composite samples

Table 2. Weight % of various compositions of natural fibers

Sample code	Epoxy (wt.%)	Coir (wt.%)	Hemp (wt.%)	Kapok (wt.%)
Epoxy	100	--	--	--
A	50	25	25	0
B	50	25	0	25
C	50	25	5	20
D	50	25	20	5
E	50	25	15	10
F	50	25	10	15

2.3. Tensile Test

Tensile tests are routinely performed on flat objects. The specimen has dimensions of 20 mm wide and 3 mm thick. The composite sample underwent tensile testing with standard specimens per ASTM D638-14 on a universal testing machine (MCS/UTE-1T, Hyderabad, India). The velocity is contingent upon the specimen's configuration and varies from 1.27 (low speed) to 254 mm (medium speed) per minute. A strain rate (ε) of 1.389 x 10^{-5}/s was employed to test the tensile testing of mechanical properties at a loading rate. The designated duration from the commencement of the test until the break has been extended from 30 to 35 minutes. The atmospheric testing temperature is 28±2 °C with a relative humidity of 50 ± 10%. A contact extensometer with a ±5% strain range is typically sufficient for optimum results; however, high-elongation variations may be required for ductile composites. The extensometer clips onto the sample and records displacement with precision, often in the range of ±1 μm resolution, assuring little error when compared to crosshead-based measurements. The extensometer is especially useful for natural fiber composites, which frequently have low stiffness (1-10 GPa) and moderate elongation (1-5%). It captures the first elastic region and early plastic deformation before being removed immediately before fracture to avoid damage. Standard testing protocols (such as ASTM D3039 or ISO 527) specify that composites be tested with an extensometer with a gauge length of 60 mm. The observed displacement is then transformed into strain by dividing by the original gauge length, allowing precise determination of Young's modulus and stress-strain behavior.

2.4. Flexural Test

A universal testing apparatus was employed to perform the flexural test on the composite specimen. The specimen has a width of 20 mm and a thickness of 3 mm. The flexural test standard adhered to is ASTM D790-10 (MCS/UTE-1T, Hyderabad, India). The testing velocity varies from 0.05 to 0.1 m/min, with a span distance of 10 to 200 mm.

2.5. Impact Test

The impact test is conducted utilizing a Tinius Olsen testing machine, and the test specimens are fabricated in accordance with the ASTM-D256-10 standard dimensions. The measurements of the Izod test specimen are 60 mm x 15 mm x 3 mm. The Izod impact test consists of a pendulum with a specified weight at the end of its arm, which swings downward to strike the specimen placed vertically in a secure manner. The schematic drawings of mechanical testing samples and testing apparatus are illustrated in Fig. 5 and Fig. 6, respectively.

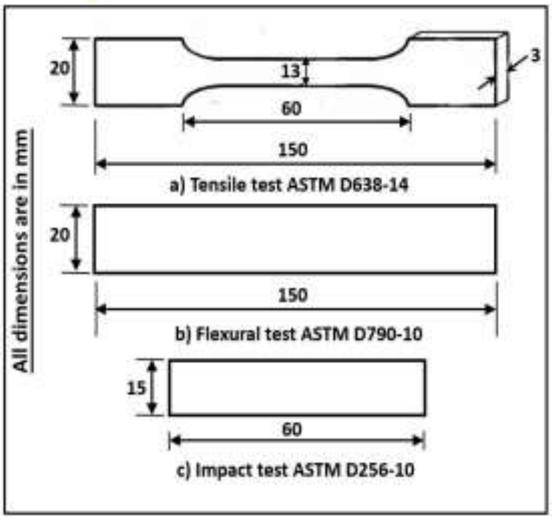


Fig. 5. Schematic drawing of testing samples

a. Ductile tester, b. Bendable tester, c. Impact tester
D. hardness tester (Shore-Durometer)
Fig. 6. Testing apparatus

2.6. Hardness Test

The sample's hardness was measured with a Shore-D hardness tester (50293 HTR-I Hyderabad, India). The testing was conducted in compliance with ASTM D785. The hardness tester features a 1.40 mm diameter and a 30º conical indenter that extends to a depth of 2.54 mm. For each sample, a minimum of three measurements were obtained from different locations, and an average value was computed.

3. Results and Discussion

3.1. Tensile Strength

The fibers employed in the samples are coir, hemp, and kapok, each with its own set of mechanical properties. Hemp is known for its exceptional tensile strength and stiffness, coir adds volume but is generally less strong, and kapok is lightweight but relatively weak. According to the test results, the epoxy sample has very low values of 36.21 MPa. When compared to other composite samples, this one has lower strength. Epoxy is inherently brittle and lacks ductility. Under tensile loading, pure epoxy fractures quickly due to its low toughness and inability to withstand high stress. Adding fibers enhances the qualities of the composite material, which initially lacks surface functionality and dispersion.

Sample A, which is 50% epoxy, 25% coir, and 25% hemp, has a tensile strength of 64.04 MPa, as shown in Fig. 7, indicating a balanced reinforcement in which the strong hemp fibers give high structural integrity while the coir contributes wt.% without appreciably weakening the composite. The tensile strength of Sample B, which contains 25% kapok but no hemp, is reduced to 59.36 MPa. Despite the inclusion of coir, the high content of kapok diminishes overall strength due to its weaker mechanical qualities when compared to hemp. Sample C, which contains 5% hemp and 20% kapok, has a tensile strength of 61.06 MPa, which is somewhat greater than Sample B, because the addition of hemp helps to reduce the weakening impact of kapok. Samples D, E, and F exhibited superior tensile strengths compared to the initial three, owing to the increased hemp content. Sample D, comprising 25% coir, 20% hemp, and 5% kapok, exhibited the highest tensile strength of 66.28 MPa, owing to hemp's significant improvement of the composite's tensile resistance [5]. Similarly, Sample F, comprising 10% hemp and 15% kapok, exhibits a tensile strength of 65.13 MPa, whereas Sample E, including 15% hemp and 10% kapok, demonstrates a strength of 62.14 MPa. These findings show that enhancing hemp content, especially when reinforced by a minimal quantity of kapok, enhances tensile strength. The superior mechanical strength and stiffness of hemp significantly enhance the composite, but kapok fibers, despite their lower strength, do not substantially influence overall performance unless present in large weight percentages. The overall trend of these results emphasizes the need to balance the fiber types in the composite, with hemp being the primary contributor to tensile strength, while the presence of kapok should be avoided for best mechanical performance.

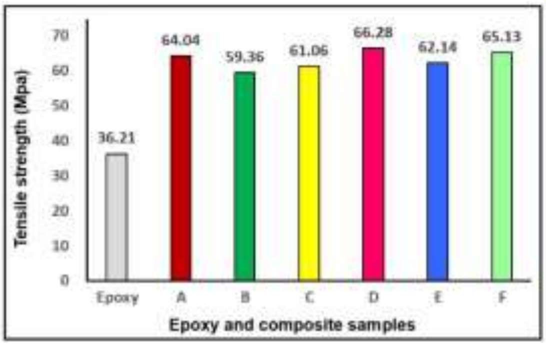


Fig. 7. Tensile strength of samples

3.2. Flexural Strength

The matrix in the offered samples is epoxy, and the fibers are coir, hemp, and kapok, each of which contributes to the mechanical qualities differently. Hemp, being strong and stiff, greatly increases both tensile and flexural strength, whereas coir offers volume and a degree of reinforcement, and kapok, being lightweight and less stiff, often diminishes strength when present in large quantities. Figure 8 depicts the bending strength of epoxy and composite samples. Epoxy is inherently brittle and lacking in ductility. When subjected to flexural (bending) loads, it splits and collapses quickly with little deformation. It has little resistance to crack propagation, resulting in early failure. Because of this, the epoxy sample has a lower strength of 98.13MPa when compared to other composite samples.

Sample A, which is made up of 50% epoxy, 25% coir, and 25% hemp, had the maximum flexural strength at 126.58 MPa, as shown in Fig. 8. This is owing to the well-balanced combination of coir and hemp, in which hemp fibers provide significant reinforcement and successfully withstand bending stress. The absence of kapok assures that there is no weakening impact, resulting in a robust, well-balanced composite. Sample B, which contains 25% kapok but no hemp, has a flexural strength of 118.19 MPa. The high presence of kapok, which is weak in comparison to hemp, diminishes the composite's overall capacity to resist bending stresses, resulting in a drop in flexural strength. Sample C, which contains 5% hemp and 20% kapok, has a flexural strength of 110.8 MPa, suggesting a further decrease due to the high concentration of kapok [10]. While hemp adds some support, the high quantity of kapok reduces the composite's bending resistance. Sample D, which contains 20% hemp and 5% kapok, has the highest flexural strength of all of the samples, at 138.92 MPa.

This is due to a considerable increase in hemp content, which increases the composite's bending resistance by producing strong, stiff fibers that are highly effective at dispersing stress throughout the material. Samples E and F exhibit flexural strengths of 122.77 MPa and 128.12 MPa, respectively. Both reveal lower hemp content than Sample D; however, they still possess commendable flexural strength due to the inclusion of hemp. Sample E, including 15% hemp and 10% kapok, has reduced flexural strength compared to Sample D, due to the higher kapok concentration that diminishes bending resistance. Sample F, which contains 10% hemp and 15% kapok, maintains a reasonably good flexural strength; however, it is significantly lower than Sample D's due to the higher kapok content. The results reveal that increasing the hemp content improves the flexural strength of the composite because hemp fibers are robust and stiff, contributing significantly to bending resistance. Kapok, on the other hand, diminishes flexural strength because of its inferior mechanical qualities, especially when present in larger proportions. Sample D looks to have the best balance for flexural strength, with a higher proportion of hemp and the least quantity of kapok, resulting in the highest flexural strength.

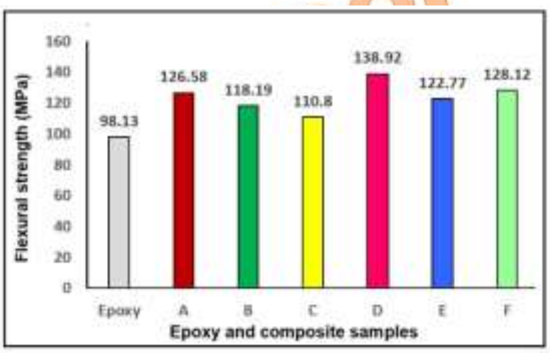


Fig. 8. Flexural strength of samples

3.3. Impact Strength

The impact strength of composite materials is largely reliant on the fiber content, fiber type, and interaction between the fibers and the epoxy matrix. In the provided samples, the impact strength of the composite is influenced differently by the fibers, kapok, hemp, and coir, as seen in Fig. 9. In these impact results, epoxy shows only 3 J/m². In comparison to other composite samples, this one has a low impact strength. The explanation is that pure epoxy is a brittle polymer with little toughness. When subjected to an impact load, it cracks and breaks catastrophically with minimal energy absorption. There is no reinforcement to prevent crack initiation and propagation.

Sample A, which is made up of 50% epoxy, 25% coir, and 25% hemp, has the maximum impact strength at 7 J/m². This outcome is the consequence of a well-balanced coir and hemp combination. Coir gives flexibility and durability, while hemp, a strong and stiff fiber, adds to the composite's total strength. Because kapok is less stiff and would typically reduce toughness, its absence guarantees that the composite maintains a respectable balance between strength and impact resistance. The impact strength of Sample B, which has no hemp but 25% kapok, is 6 J/m². Kapok is a lightweight fiber, but it is weaker and less rigid than hemp, which reduces the composite's capacity to absorb impact energy effectively. Although coir contributes to some toughness, the absence of hemp and the presence of kapok reduce impact strength when compared to Sample A. Sample C, composed of 5% hemp and 20% kapok, has an impact strength of 5 J/m². Kapok fibers are not as effective at absorbing impact energy as hemp; hence, the high proportion greatly reduces the composite's capacity to withstand rapid shocks. The modest amount of hemp in this sample contributes marginally to overall strength, but not enough to offset the impact reduction produced by the high proportion of kapok [11-13]. Sample D, consisting of 20% hemp and 5% kapok, has the highest impact strength of 9 J/m². The additional hemp in this sample improves the composite's capacity to absorb impact energy and resist fracture. Hemp's strength and stiffness, mixed with the smallest amount of kapok, create a strong composite that performs well under abrupt stresses.

The reduced amount of kapok gives the material certain lightweight qualities while also enhancing its durability. Samples E and F exhibit impact strengths of 6 J/m² and 8 J/m², respectively. Sample E, with 15% hemp and 10% kapok, has moderate impact strength due to the balanced presence of hemp and kapok, but the higher concentration of kapok limits its ability to absorb impact energy when compared to Sample D.

The impact strength of Sample F, which contains 10% hemp and 15% kapok, is higher than Sample E because the lower kapok content maintains more toughness in the composite, even if the hemp percentage is somewhat lower. The results demonstrate that increasing hemp content improves impact strength because of its high strength and stiffness, which contribute to enhanced energy absorption and toughness. Kapok, on the other hand, diminishes impact strength when in large quantities due to its weak and less rigid nature. Sample D has the highest impact strength due to a higher proportion of hemp and a low amount of kapok, allowing the composite to maintain good toughness while efficiently resisting impact loads.

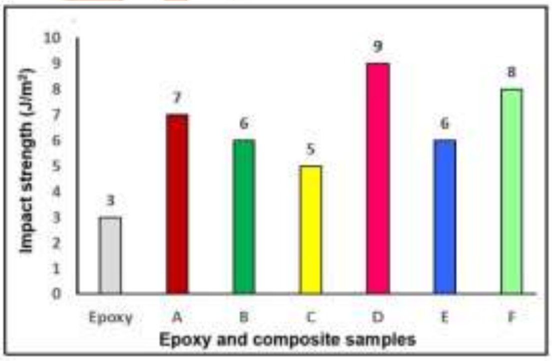


Fig. 9. Impact strength of samples

3.4. Hardness

The fibers utilized in the offered samples include coir, hemp, and kapok, each with their own mechanical qualities that affect the hardness of the composite, as shown in Fig. 10. Epoxy sample hardness is 43.14. This result is quite low when compared to other composite samples. Epoxy is a polymeric substance with relatively low hardness and stiffness. When indented, pure epoxy deforms more easily than fiber-reinforced composites. Also, more prone to plastic deformation under applied load.

Sample A, consisting of 50% epoxy, 25% coir, and 25% hemp, had the maximum hardness rating of 71.67. The balanced blend of coir and hemp is responsible for this result. Hemp, as a strong and rigid fiber, contributes significantly to the composite's hardness, whereas coir adds flexibility but does not appreciably affect the composite's total hardness. The composite's high hardness is ensured by the absence of kapok, which could lessen the material's resistance to surface deformation. Sample B has a hardness of 61.76 with 25% kapok and no hemp. The overall hardness of the composite is decreased by kapok, a lighter and softer fiber that lacks hemp's stiffness and strength. Thus, in contrast to Sample A, which has a stronger hemp reinforcing fiber, the material's ability to withstand surface indentation is diminished. Sample C, which contains 5% hemp and 20% kapok, has a hardness of 58.35. Because kapok fibers are fragile and provide modest reinforcement, their high proportion in this sample greatly reduces the composite's resistance to indentation. The modest amount of hemp in the sample adds stiffness, but it is inadequate to offset the softening impact of the kapok fibers. Sample D, which contains 20% hemp and 5% kapok, had the maximum hardness of the samples (74.18). The higher amount of hemp in this sample increases hardness because hemp's strength and stiffness improve the composite's resistance to surface indentation [14]. The small amount of kapok in this sample significantly enhances its hardness, resulting in the greatest hardness rating (Sample D). Hardness values of 68.64 and 72.12 are reported for samples E and F, respectively. Sample E, which contains 15% hemp and 10% kapok, has a moderate hardness since the hemp still contributes significantly, while the higher kapok percentage lessens the composite's total hardness. Sample F, with 10% hemp and 15% kapok, has a hardness of 72.12, which is higher than Sample E, most likely due to the smaller amount of kapok, keeping more of the composite's stiffness and hardness.

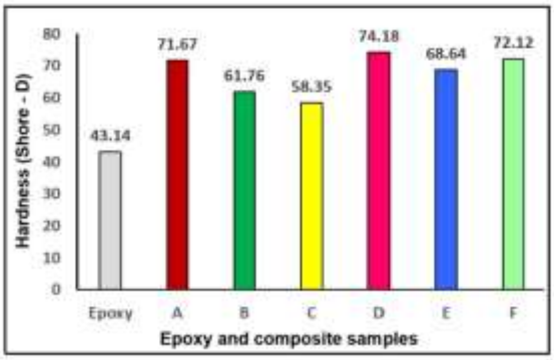


Fig. 10. Hardness of samples

The findings show that the presence of hemp generally increases the hardness of the composite due to its robust and rigid nature, which resists surface deformation. Kapok, a softer and lighter fiber, lowers hardness when present in larger volumes. Sample D has the highest hardness, thanks to a higher proportion of hemp and less kapok, which ensures the composite's strength and resistance to surface indentation.

3.5. Morphological Study

The micrographs clearly show that the three fiber-reinforced epoxy composites are mixed uniformly. The first scenario, Fig. 11 (A), represents that delamination, epoxy damage, and voids are the three most common damage mechanisms. Delamination, as shown in the upper rectangular section, represents the separation of layers inside the sample, which is most likely caused by weak interfacial bonding or severe interlaminar stress. The epoxy damage seen at the lower left indicates localized cracking or rupture in the matrix phase, which is significant since the epoxy acts as a load-transferring medium between layers. The existence of voids, which appear as small, dark, round patches, suggests that resin infiltration was incomplete or that air was trapped during the cure process.

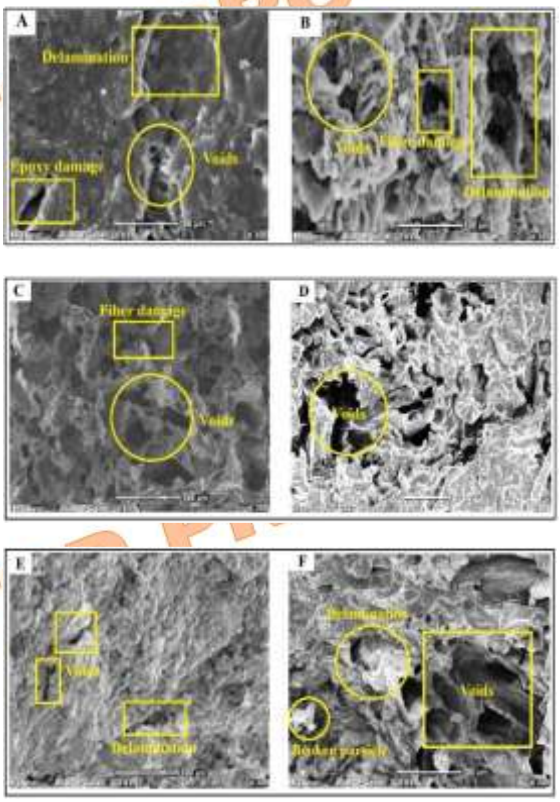


Fig. 11. Morphological images of composite samples

These voids operate as stress concentrators, reducing the load-bearing capability of the composite substantially. Figure 11 (B) shows delamination, fiber damage, and voids, but the surface morphology is rougher than in Image A, which could be owing to a different loading situation or fiber-matrix interaction. The voids in this image appear more irregular and crowded, which may jeopardise the material's integrity. Fiber damage has reappeared, indicating that fiber-matrix adhesion problems persist. The detected delaminated spots in B also indicate interfacial failure, which contributes to the composite's overall structural degeneration. The fiber damage observed in the rectangular highlighted region indicates that the fibers broke or debonded from the surrounding matrix, as shown in Fig. 11 (C). This indicates a poor fiber-matrix interface or high stress caused by mechanical loading. The presence of clearly visible voids in the circular zone indicates manufacturing flaws such as incomplete resin impregnation or trapped air during composite manufacture. These voids reduce the composite's mechanical strength by acting as stress concentrators and crack initiation locations. Figure 11 (D) shows improper matrix bonding on the sample as a result of minor voids in the epoxy and matrix reinforcement. Furthermore, the remaining part of the sample D reveals that the higher interfacial stress transmission was attributable to improved fiber-matrix adhesion. Because alkalization roughens the fiber surface, greater mechanical anchoring effects contribute to good adhesion between alkali-treated fiber and epoxy matrix. The fibers are embedded within the matrix, and for optimal performance, the load must be transferable to the fiber, requiring a robust fiber/matrix bond. In epoxy lattice composites, it is expected that the compound responses at the interface, specifically epoxy ring-opening and the formation of covalent bonds with the fiber, are crucial for interfacial adhesion. Corrosive base communications and hydrogen interactions between the alleviated epoxy structure and the fiber surface can enhance adhesion [15-17]. The elimination of solidification during dewaxing and alkali treatment, leading to a cleaner and less desirable fiber surface, facilitates the establishment of a solid interphase. It also improves mechanical interlocking with the framework [18] and the resin's wettability on the NaOH-treated fiber surface. An increased surface area may enhance interfacial adhesion. The enhanced interaction between NaOH-treated fibers and epoxy matrices results from a cleaner, rougher fiber surface produced by dewaxing, along with the development of a more resilient interphase. It also improves mechanical interaction between the matrix and resin adhesion on the NaOH-treated fiber surface. The intrinsic variety in the qualities of natural fibers, including variations in fiber length, diameter, and strength, can cause unequal load distribution, resulting in localized stress concentrations that favour breakage and the formation of fragmented particles. In Sample D, which is 50% coir, 5% kapok, and 20% hemp, the combination of natural fibers with varying surface textures and aspect ratios creates a diversified interfacial environment. Coir, being a coarse and hard material, provides structural stability, whereas kapok, with its finer and hollow fiber structure, aids in matrix interaction. Hemp contributes because of its high cellulose content and mechanical strength. The alkali treatment of these fibers eliminates surface contaminants and waxes, exposing hydroxyl groups that can chemically interact with the epoxy matrix, resulting in better covalent bonding and hydrogen bonding at the interface. These modifications not only reduce surface roughness but also dramatically increase interfacial shear strength (IFSS) by enhancing both chemical bonding and mechanical interlocking at the interface. The increased IFSS in sample D complements the SEM findings, demonstrating that stress is easily transferred from the matrix to the fiber, which is important for load-bearing capacity. Thus, IFSS is a reliable scientific metric for validating the increased interfacial adhesion observed morphologically, particularly in hybrid natural fiber composites like Sample D. Poor fiber treatment prior to composite integration may worsen the situation. One of the key causes of matrix debonding is a poor interaction between hydrophilic natural fibers and typically hydrophobic matrix materials. Voids in natural fiber composites are frequent during the production process, especially when the fibers are not entirely immersed in the matrix material. Inadequate resin flow or mixing can cause air pockets and cavities inside the composite [19-21]. Two principal faults are seen in Fig. 11 (E): voids and delamination. The voids, represented by rectangular boxes, indicate areas where trapped air or insufficient resin wetting happened during the production process. These flaws decrease load-bearing capacity by serving as stress concentrators [22-24]. The delamination shown in the lower portion of the photograph indicates material layer separation, which is often caused by weak interfacial bonding or shear stress during loading. This type of failure degrades structural integrity and causes composites to fail prematurely when subjected to mechanical loads [25-27]. Figure 11 (F) depicts more complex failure morphology, with three distinct features: delamination, fractured particles, and voids. The delamination zone in the upper central region suggests interlayer separation, implying a breakdown in fiber-matrix adhesion. The presence of broken particles in the lower left corner suggests that some filler or reinforcement particles shattered under stress, either due to brittle behavior or localized overloading. The wide void zone on the right side is noteworthy, indicating substantial resin flow difficulties during manufacture, which resulted in insufficient impregnation and material weakness.

3.6. Void Content Measurement

The void content analysis reveals important information about the quality and structural integrity of epoxy and fiber-reinforced composite materials. Table 3 summarises the void content of all samples. Calculate the void content (V_v for your composite samples, using the formula:

$$V_v(\%) = \frac{\rho_t - \rho_c}{\rho_t} \times 100 \tag{1}$$

where:
ρ_t = Theoretical density (based on weight fractions and individual material densities)
ρ_c = Measured composite density (experimental value)

Table 3. Void contents of samples

Sample	Void content (%)
Epoxy	1.02
Sample A	3.08
Sample B	3.57
Sample C	2.85
Sample D	2.42
Sample E	5.41
Sample F	2.63

In this study, the pure epoxy sample had a low void percentage of 1.02%, indicating that the resin was well-cured and had minimal trapped air or flaws. However, the fiber-reinforced samples had various void content values, with Sample A having 3.08% void content, Sample B having 3.57%, Sample C having 2.85%, Sample D having 2.42%, Sample E having 5.41%, and Sample F having 2.63%. Sample E had the largest void percentage (5.41%), indicating increased porosity due to insufficient fiber-matrix interaction, air pockets, or poor resin dispersion. This could result in lower load-bearing capability and weaker interfacial bonds. In comparison, Sample D had the lowest void content of the fiber-reinforced composites (2.42%), indicating greater fiber dispersion and matrix wetting, which improved mechanical performance. Samples A, B, C, and F had moderate void content levels, implying that fiber composition and processing circumstances influenced porosity.

4. Conclusions

The following results are drawn from the experimentation of green waste fiber composites for engineering applications:

- Pure epoxy sample has reduced tensile strength due to the lack of structural support, rendering it susceptible to rapid failure under tension. Similarly, the epoxy sample deforms and splits when subjected to flexural loads because of its brittleness. However, the epoxy sample fails catastrophically when subjected to a sudden impact because of its low hardness and rapid crack propagation. Because of its softer and more malleable nature, pure epoxy has lower hardness than fiber-reinforced composites.
- Sample D, with 5% kapok and 20% hemp, shows considerable improvement in tensile (66.28 MPa) and flexural strengths (138.92 MPa), as well as a greater impact strength of 9 J/m². This shows that a small amount of kapok (5%wt.) improves overall material performance, possibly due to better energy absorption from kapok fibers, while retaining structural integrity. Sample D also has the maximum hardness (74.18 Shore D), demonstrating that kapok helps to increase the material's indentation resistance. Sample D's 25% coir fiber made significant contributions to improving the mechanical properties of the composite. The high lignin concentration of coir increases its tensile and flexural strength, making it more robust and resistant to deformation. Its inherent hardness and suppleness aid in absorbing impact energy, resulting in improved impact strength. Coir fibers also link well with the epoxy matrix, increasing hardness and overall structural integrity. The addition of 25% coir provides a well-balanced reinforcement, making the composite stronger, more resilient, and more suited for load-bearing uses.
- Sample F (containing 15% kapok) has tensile and flexural strengths of 65.13 MPa and 128.12 MPa, respectively, with an impact strength of 8 J/m² and a hardness of 72.12 Shore D. While more kapok concentration may reduce tensile and flexural performance, the material's impact resistance and hardness remain high.
- Adding kapok fiber to epoxy-coir composites has a complex impact on mechanical characteristics. A modest amount of kapok, as seen in Sample D, improves the tensile, flexural, and impact properties; however, excessive amounts may reduce strength while retaining beneficial impact resistance and hardness. As a result, the content of kapok fibers should be tuned based on the required balance of strength and impact resistance for individual applications.
- Delamination, as seen in pictures A, B, E, and F, indicates poor interfacial bonding

between layers or matrix and fiber, which is frequently caused by unequal stress distribution or insufficient curing. This layer separation has a significant impact on the structural stability of the composite.

- Morphological studies indicate interfacial interactions between fibers and matrix. It also represents the bonding properties of the various fiber-reinforced epoxy materials.
- The high mechanical properties suggest that the resultant composites are cost-effective, lightweight, and ecologically benign for a range of applications.

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Conflicts of 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.

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