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Article

Coir powder-reinforced epoxy resin composites: Fabrication and characteristics analysis

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Abstract: In order to replace conventional materials in the existing composite world, there has been a focus on adopting coir fibres, which are lightweight, adaptable, efficient, and have great mechanical qualities. This study describes the creation of environmentally responsible bio-composites with good mechanical characteristics that employ coir powder as a reinforcement, which has good interfacial integrity with an epoxy matrix. And these epoxy-coir composites supplemented with coir particles are predicted to function as a reliable substitute for traditional materials used in industrial applications. Here, untreated and alkali-treated coir fibres powder were employed as reinforcement, with epoxy resin serving as a matrix. An experimental investigation has been carried out to study the effect of coir powder reinforcement at different weight percentages (5 wt%, 10 wt%, 15 wt%, 20 wt%, 25 wt%, and 30 wt%). The morphological study, followed by a scanning electron microscope (SEM) and an optical microscope (OM), demonstrated that the powder and matrix had the strongest adhesion at 20 wt% coir powder-reinforced composite, with no voids, bubbles, or cracks. Based on the entire investigation, the polymer composite with 20 wt% reinforcement exhibited better mechanical qualities than the other combinations.

Keywords: composite; coir powder; epoxy resin; mechanical properties; SEM

1. Introduction

Over the last several years, a number of scholars have been researching the use of natural fibres as load-bearing elements in composite materials. Composite material is a multi-phase system composed of matrix and reinforcing materials. The matrix specifies the volume of the composite material, combines the reinforcing agent, and uniformly distributes the applied load to reinforcements, giving strength and stiffness for structural loads.

Polymer matrix composites (PMCs) are powder-reinforced polymers in which a thermoset or thermoplastic polymer serves as the matrix. Polymer matrix composites (PMCs) are often used in a variety of sectors, including vehicles, ships, and structural applications, due to their high strength-to-weight ratio, simplicity of manufacture, and low cost [1,2]. Polymeric composites can be reinforced with synthetic fibres such as glass, carbon, boron, graphite, or natural fibres including sisal, hemp, flax, bamboo, coir, and jute. Natural fibre composites are suitable for building [3,4], packing [5–7], car interiors [8,9], and storage equipment due to their low density, environmental benefits, and cost-effectiveness [10].

After the flesh of the coconut and sap are removed, leftover shells are used to create coir fibres, a common natural fibre [11]. Brushes, carpets, and other everyday items were traditionally made from the majority of coir fibres [12,13]. The application of coir fibres as reinforcing fibres in composite materials has been the subject of increased investigation in recent years [14]. Therefore, using coir fibres is not only a good technique to repurpose coconut waste but also a means to lessen the environmental problems produced by the buildup and burning of waste coconut shells. Not only do coir fibres increase the toughness of epoxy resin, but they also have good mechanical qualities, with the best elongation of any known natural fibre. It can be utilised as a reinforced material because it is non-toxic, inexpensive to manufacture, high in lignin content, and strong [15]. Coir fibre includes 45.84% lignin, 43.44% cellulose, and 0.25% hemicellulose [16]. The water that has been adsorbed into the hydrophilic coir fibre's lignocellulosic surface hinders efficient adhesion to the hydrophobic polymer matrix, affecting the mechanical efficacy of polymer composites for any fibre volume fraction. However, there are potential ways to reverse this decreasing mechanical property condition. Here, the scholar relied on an alkali process for treating the surface of the coir fibre. A strong alkali treatment boosts coir fibre adherence to the polyester matrix, elevating composite strength by around 50% for a 30% coir fibre volume fraction [17].

In this research, coir powder-reinforced polymer composites contain both untreated and alkali-treated coir powder. Alkali treatment raises strength, lowers impurities, and improves the interfacial bonding ability by removing some non-cellulosic substances from the fibres and increasing the surface roughness of the fibres, which brings benefits such as lightweight, high strength, simple manufacture, and superior insulation [18–20]. The efficacy of coir powder-reinforced composites is assessed by alkali treatment. After the experiment, alkali-treated composites would show greater mechanical qualities [21].

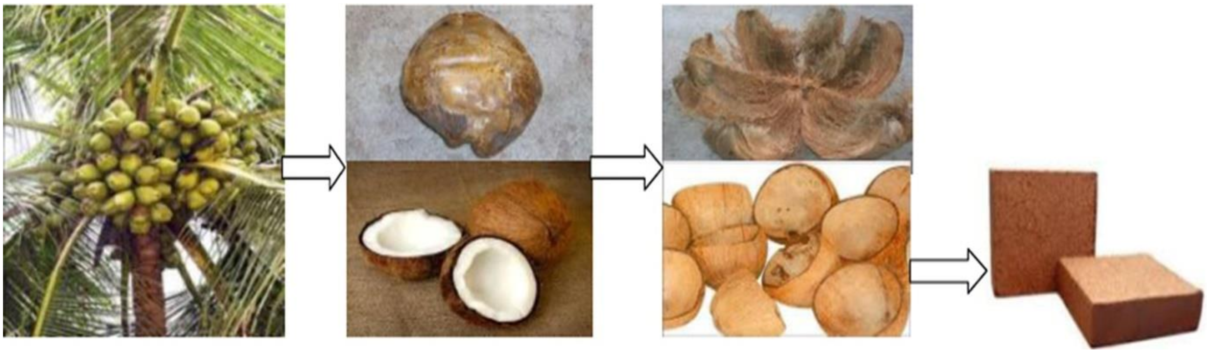

Figure 1. Formation of coconut fibre bio-composite material [22].

In this study, epoxy resin is utilized as a composite matrix due to its great strength and adhesiveness. It is comprised of amorphous, highly cross-linked polymers, which provide these materials with excellent features such as high tensile strength and modulus, ease of manufacturing, strong thermal and chemical resistance, and dimensional stability. However, it results in low hardness and poor fracture resistance [23]. Epoxy resins are used in a variety of applications, including general-purpose adhesives [24], binder in cements and mortars [25], the production of hard foams [26], industrial paints and coatings [25,27], and more [28].

The mechanical characteristics of a natural fibre powder-reinforced composite are influenced by powder particle size, modulus, and distribution. A robust powder-matrix interface connection is vital to maximizing the composite's strength and optimum stress transfer from the matrix to the reinforcement powder [29]. This study analyzes several combinations of untreated and treated coir fibre power with thermoset epoxy resin composites (**Figure 1**). The fabrication of the composite samples is done by hand-layup process. The distribution of reinforcement in matrix resin is investigated through an optical microscope (OM) and a scanning electron microscope (SEM). The mechanical properties were also measured using a universal testing machine (UTM). We applied a different treatment to the coir fibres because there are several methods for handling natural fibres. In order to improve the interfacial bonding capabilities of coir-fiber-reinforced epoxy resin composites, we also made coir fibre to particle and compared different test results to find a more suitable procedure that enhanced the compatibility between coir powder and the matrix.

2. Materials and methods

2.1. Materials

A thermoset epoxy resin was employed as the matrix, along with a hardener. Those were gathered from Nasim Plastic in Dhaka, Bangladesh. Epoxy resin has a molecular weight of 393 Da, a viscosity of 9–14 Pa·s, a density of 1160 kgm^{-3}, and a flash point above >150 ℃. The hardener had a molecular weight of 305 Da, a viscosity of 0.45 Pa·s, a density of 900 kgm^{-3}, and a flash point of 129 ℃. Coir fibre was collected as waste material for coconut from local sources. Pellets of sodium hydroxide (NaOH) were obtained from MERCK in Mumbai, India. It had a purity level of 97.16%.

2.2. Chemical modification of coir fibre

Alkali treatment

Initially, coir fibre was split into little pieces of around 2 inches. The fibres were washed using distilled water. Then the fibres were treated with a 5% NaOH solution at room temperature for 60 min, keeping the liquid to fibres ratio at 15:1. After 1 h, the fibres were carefully cleaned with distilled water three times. The cleaned fibre was then dried in the sun and air. Following that, moisture was removed from treated fibres using a hot air oven set at 105 ℃. The alkali-treated coir fibres were ground into powder using a Panasonic mixer grinder (model MX-AC400). The particles were passed through filters with sieve no. 70 and apertures of 210 microns (**Figure 2**).

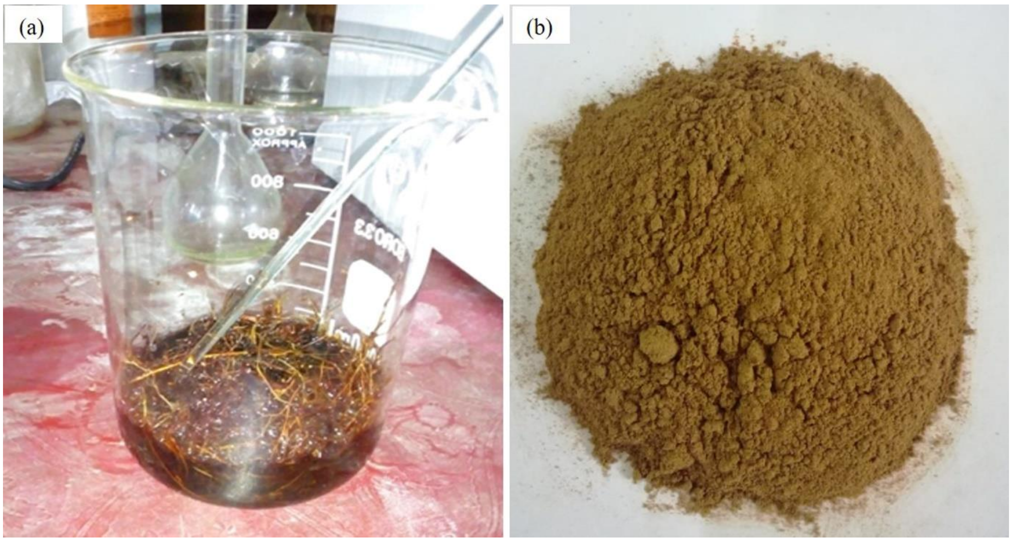

Figure 2. (a) Alkali treatment of coir fibre; **(b)** Alkali treated coir fibre powder.

2.3. Untreated of coir fibre

The untreated coir fibres were ground into powder using a Panasonic mixer grinder (Model MX-AC400). The powders were passed through filters with sieve no. 70 and apertures of 210 microns (**Figure 3**).

Figure 3. Untreated Coir fibre powder.

2.4. Composite preparation method

Epoxy resin, an example of an epoxy oligomer, creates a three-dimensional structure when complemented with a hardener or curing agent. Epoxy resin characteristics may be changed by using different epoxy oligomers and curing processes. The weight ratio between epoxy resin and hardener was 10:1. At first resin and hardener mixed well with super hand mixer (Model: HE-133, Scarlett, England). After that the alkali-treated coir powder at various weight percentages (5 wt%, 10 wt%, 15 wt%, 20 wt%, 25 wt%, and 30 wt%) was blended with epoxy resin utilizing super hand mixer. To manufacture one type of composite at a time, a 100-gram matrix and reinforcement combination were utilized. The matrix, containing 95 gm epoxy resin, and 5 gm coir fibre powder, was blended and stirred for 5 min to generate 5 wt% of reinforcement. Again, for 10 wt%, 15 wt%, 20 wt%, 25 wt%, and 30 wt%, the taken weight of matrix was 90 gm, 85 gm, 80 gm, 75 gm, and 70 gm epoxy resin, respectively. The composite was cast using a mould with dimensions of 3mm × 10mm × 80 mm. The mould was waxed with a releasing agent before being filled with a resin-powder mixer. The releasing agents utilized serve to prevent the sample from sticking or becoming lodged inside the mould, as well as allowing for simple removal of the sample. The samples were stored in the mould for 24 h before testing (**Figure 4**).

The same hand-lay technique was used to make composites from untreated coir fibre powder. Mix untreated coir fibre powder with epoxy at various weight percentages (5 wt%, 10 wt%, 15 wt%, 20 wt%, 25 wt%, and 30 wt%) using a super hand mixer. After that, the mixer was poured into the mould for making untreated coir powder-epoxy composites. It was also stored for 24 h for solidification.

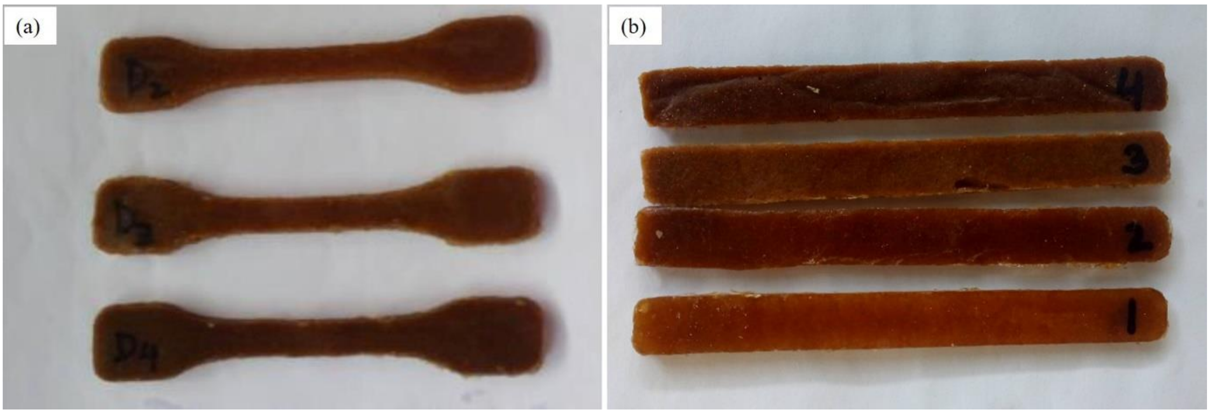

Figure 4. Images of prepared coir powder reinforced epoxy resin composite.

2.5. Microstructural analysis

The interfacial bonding between the reinforcement and epoxy matrix in the created composites was examined using optical microscopy (OM) (ML-803), Taiwan, and a scanning electron microscope (SEM) (JSM-7600 F), supplied by JEOL Company Limited, Japan. Composite samples were coated in gold before morphological analysis was done using a scanning electron microscope.

2.6. Mechanical testing

Tensile, Charpy impact, and toughness tests were performed on the materials. Five species were analyzed, and the average results were noted for each test and composite type. Tensile testing was conducted using a Universal Testing Machine (UTM) (Model: MSC-5/500, Agawn Seiki Company Limited, Japan) in accordance with ASTM D 638-01, at a crosshead speed of 10 $mm \cdot min^{-1}$. In compliance with ASTM D 6110–9724 and ASTM E23, dynamic Charpy impact tests and toughness tests were performed on notched composite specimens using a Universal Impact Testing Machine (Model: 7408, Hung Ta, Taiwan).

3. Results and discussion

3.1. Morphological observation

The microstructure of the developed composite samples was studied using an optical microscope (OM) with different magnifications (such as 10x, 40x, and 60x). The optical microstructural observations of the epoxy-alkali-treated coir powder-reinforced composite were primarily made to examine the distribution of coir particles in the polymer matrix, the presence or absence of particle clusters and agglomeration, and the presence of any inclusions and voids.

In **Figure 5**, we can see the microstructure of an 80 wt%–20 wt% epoxy-alkali-treated coir powder composite. Here, a uniform distribution of coir powder on the epoxy resin surface was observed, and no significant void, crack, or cluster was found.

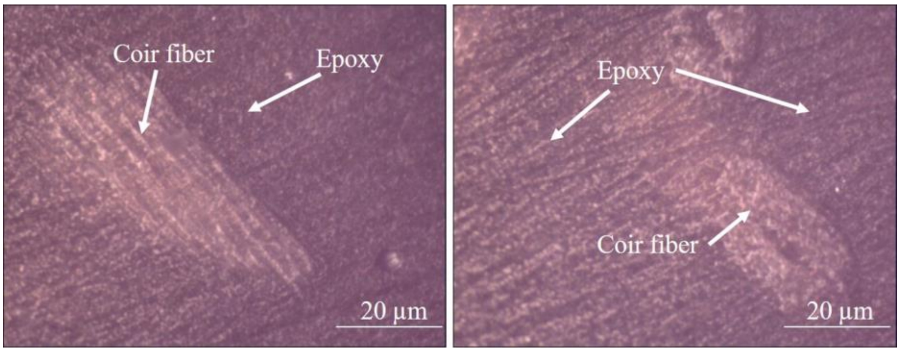

Figure 5. Optical micrographs of composite surfaces: 80–20 wt% epoxy-alkali-treated coir powder.

Scanning electron microscope (SEM) surface inspection offers substantial insights into composite samples, such as outer morphology (texture), chemical composition, interfacial adhesion, crystalline structure, and material orientation, presenting beneficial details about the specimen. This research employs SEM (scanning electron microscope) in order to generate images with high resolution along with extensive surface information from the specimen.

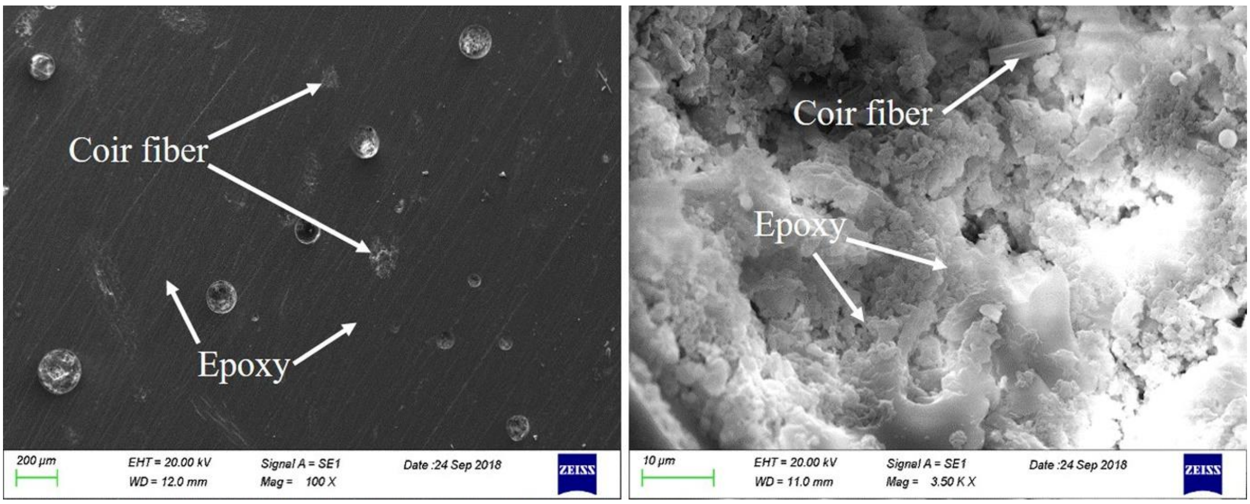

Figure 6. SEM micrographs of composite surfaces: 80 wt%–20 wt% epoxy-alkali-treated coir powder.

Figure 6 demonstrates that coir powders were embedded in a matrix with no gaps, and their surfaces were treated with polymer, which suggests strong interface bonding. Strong adhesion at the interface between the particle and polymer matrix has been observed, resulting in more effective mechanical characteristics. Coir powders were arranged on top of each other in the matrix and the particle size are around ~ 200 μm was revealed. There were no gaps, cavities, or voids, and the coir fibre and polymer were very well blended. It looks like the matrix and reinforcement composites are well bound up, and they are on track toward exhibiting considerable basic features and multifunctional textures. Based on research, the matrix in a composite is the intermediary load-bearing ingredient, while the reinforcement serves to cover the matrix and maximize its strength. A well-bonded interaction facilitates the efficient transfer and spreading of loads from the matrix to the reinforcement [30].

3.2. Mechanical properties

3.2.1. Tensile properties

Tensile strength is the maximum strain that a material tolerates without fracturing when stretched, divided by its initially formed cross-sectional area. When doing mechanical testing on polymer composites, the Universal Testing Machine (UTM) bends the sample while applying increasing tension along the material's axis. Tensile characteristics are examined at 100 $mm \cdot min^{-1}$ and the specimen was expanded using a moving crosshead.

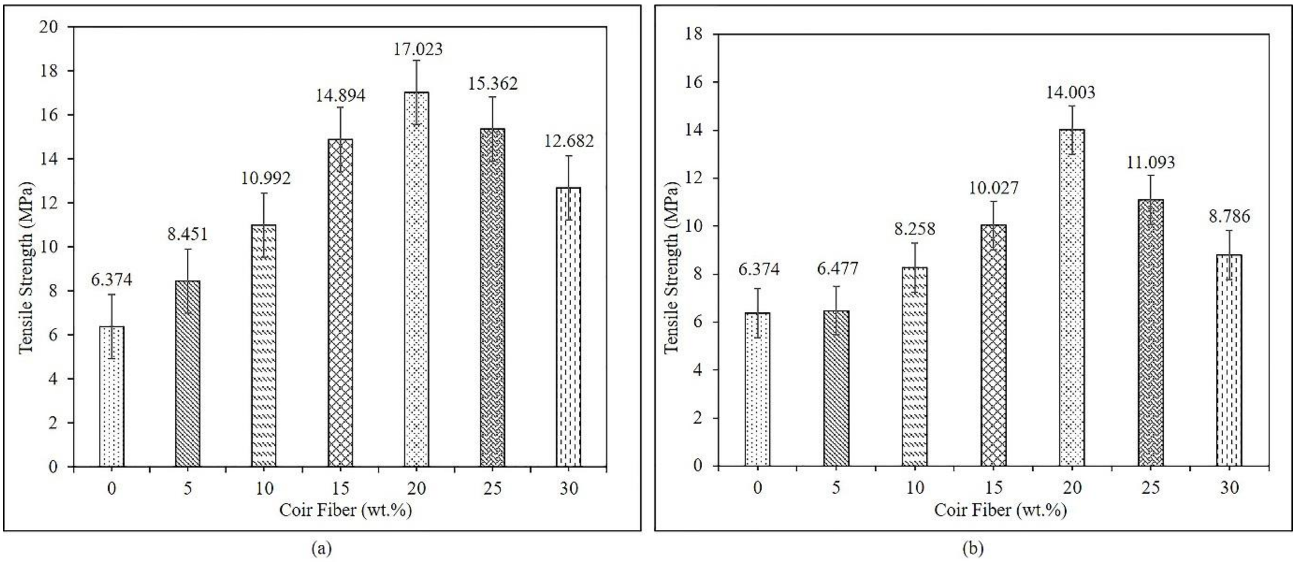

Figure 7. Tensile strength of **(a)** epoxy-alkali-treated coir powder composites; **(b)** epoxy-untreated coir powder composites.

According to **Figure 7**, enhancing the weight percentages of the powder increases the tensile strength of a composite material by up to 20 wt%. The highest recorded tensile strength of epoxy-untreated coir powder composites is 14.003 MPa, while epoxy-alkali-treated coir composites at a 20 wt% powder-to-matrix ratio possess a tensile strength of 17.023 MPa. A further increase in powder loading decreases the tensile strength. Tensile strength improves by up to 20 wt% with the loading of powder due to the powders higher load-bearing capability over the matrix. Tensile strength reduces under greater loading due to poor interfacial adhesion between powder and matrix, as well as a rise in microspace formation in composites because excessive powder generates a gap between the matrix material [31]. In addition, below 20 wt% loading may not be satisfactory for increasing the matrix's strength, and insufficient stress transfer may have resulted in a reduced strength [32].

3.2.2. Impact strength and toughness

The composite's strength, hardness, and impact energy are significantly impacted by the coconut shell particles [33]. When materials undergo an impact load, their ability to withstand fracture is gauged by their impact strength. The component material nature, the fiber/matrix interface, the composite's structure and shape, and the test circumstances all have a significant impact on the characteristics of composites that are impactful. Impact strength is correlated with the composite's higher elasticity, which in turn improved matrix deformability. As a stress-transferring medium and a means of interacting with the crack development, natural fibers often play a major part in the impact resistance of fiber-reinforced composites [34].

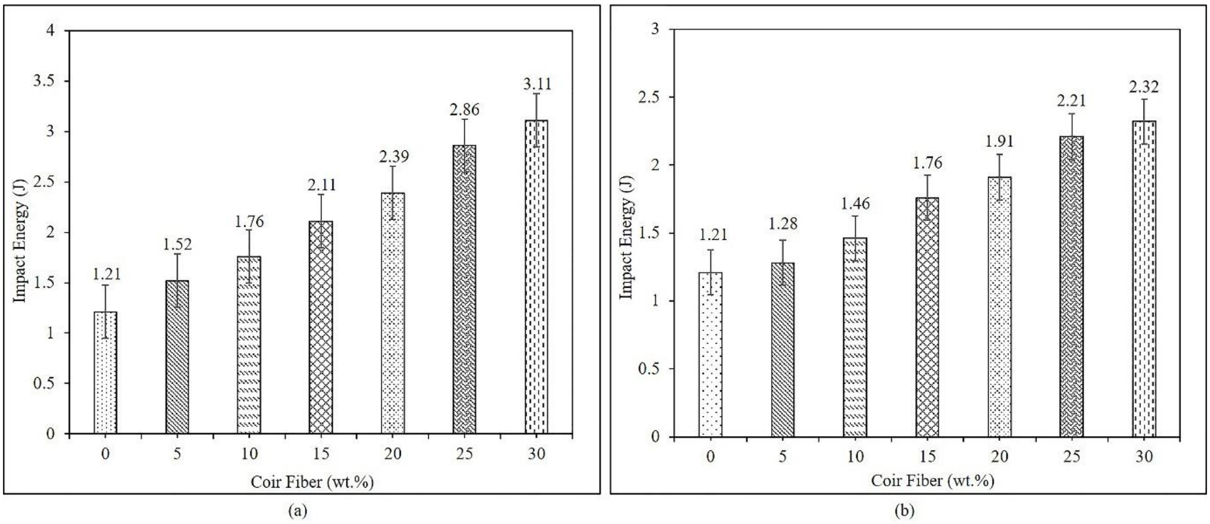

Figure 8. Impact energy of **(a)** epoxy-alkali-treated coir powder composites; **(b)** epoxy-untreated coir powder composites.

Figure 8 shows the impact characteristics of the epoxy-untreated coir powder composite compared to the alkali-treated coir powder composite. Impact energy increases with the higher loading of powder, and it reaches up to 3.11 J for epoxy-treated coir powder composites, whereas epoxy-untreated coir composites at 30 wt% percentages revealed 2.32 J. The impact energy increases with higher powder concentrations due to the larger energy absorption capacity of powders compared to matrix. This phenomenon might also be due to the good interfacial bonding of matrix to powder, which results in better energy absorption during impact [35].

Toughness is the property of the material that enables it to withstand shock and deformation without rupturing. High toughness can be achieved by a good combination of strength and ductility.

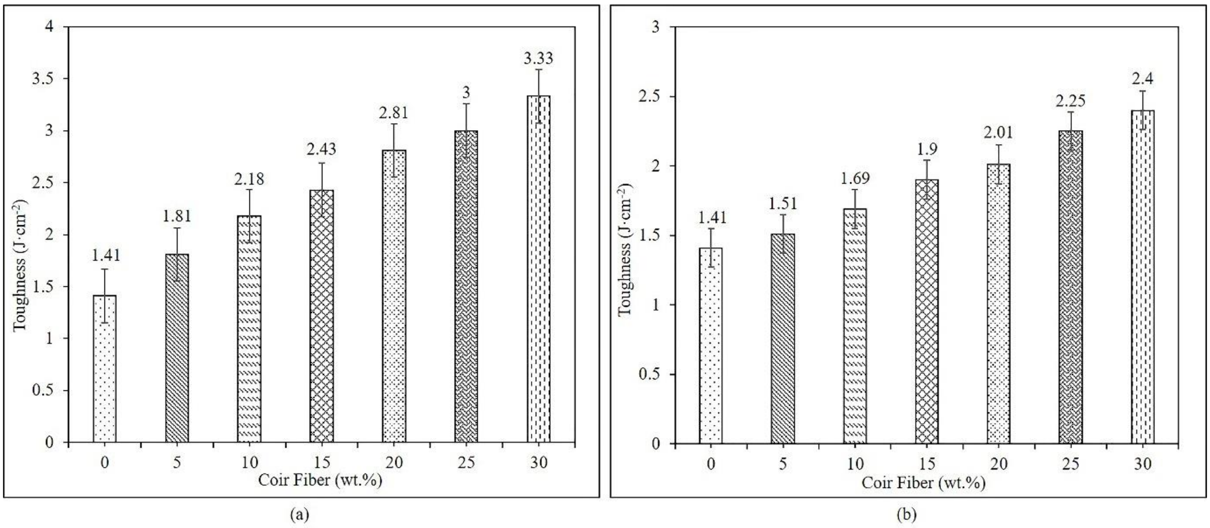

Figure 9. Toughness properties of **(a)** epoxy-alkali-treated coir powder composites; **(b)** epoxy-untreated coir powder composites.

Findings from **Figure 9** show the toughness of the epoxy-untreated coir powder composite compared to the epoxy-alkali-treated coir powder composite. The toughness of composites increases with an increase in powder concentration. However, analyzing toughness between epoxy-alkali-treated and untreated coir powder reinforcement composites shows that the improvement in toughness of epoxy-alkali-treated composites is a little more than that of epoxy-untreated coir powder-reinforced composites. At 30 wt% reinforcement composites, epoxy-alkali-treated composites exhibit 3.33 J·cm^{-2} and epoxy-untreated coir powder-reinforced composites exhibit 2.4 J·cm^{-2}. This is because alkaline treatment increases natural fibre and polymer bonding, which builds a robust structure of natural fibre with composites because of the elimination of lignin, pectin, oil, wax, and impurities on the cell wall surfaces of the fibres, which leads to the exposure of short-length crystallites and a rise in surface roughness on the fiber, which results in improved mechanical properties [36]. The alkaline-sensitive hydroxyl groups (-O-H bond structure) present in natural powder molecules are broken down by alkaline treatment. Following that, it interacted with groups of alcohol molecules, phenols, or water (H-O-H bond structure), migrating either within or outside of the powder structure in response to the alkaline reaction, depending on the properties of the powder. The cellulose molecular chain's powder cell of the -O-Na bond structure was therefore indirectly created by the residual reactive molecules, allowing the increment of mechanical properties [37].

The function of reinforcement in a composite is to contain the matrix and so improve the composites' strength, whereas the matrix's primary functioning elements are the intermediate load-bearing parts. Distribution and transmission of load from the matrix to the reinforcement are made easier by a well-bonded interface. In contrast, weak bonds restrict the amount of strengthening since they reduce load transmission. Improvements in mechanical characteristics are thus the consequence of a stronger interfacial connection [38]. In the case of the coir fibre-reinforced epoxy resin composites considered in this study, fine coir particles dispersed homogeneously on the resin matrix play an important role for good bonding of the composite. In addition, the uniformly distributed coir particles obtained by mixer grinder contribute to attaining a good compact. As shown in **Figures 5** and **6**, the interface between the matrix and the reinforcement exhibits a good interfacial integrity. Thus, it can be concluded that coir powder mixing with matrix with optimized matrix-reinforcement ratio can be very effective in improving the properties of the composite.

4. Conclusion

Composite materials are gaining popularity for their lightweight, outstanding mechanical characteristics, clarity of manufacture, and low pricing. Due to their high specific strength and modulus, powder-reinforced polymer composites, especially ones with coir fibre powder, have been frequently used. Coir fibre, an affordable and widely accessible natural fibre, can be utilized as a byproduct in coconut production for making a beneficial and useful coir powder-reinforced polymer composite. The objective of this research is to develop and explain innovative composites with untreated and alkali-treated coir fibres powder as reinforcement and epoxy resin as a matrix through a hand-lay process. The morphological observation inquiries indicate that epoxy-coir powder composites have a consistent reinforce distribution with no voids, cavities, or pores, as observed according to the Optical Microscope (OM) and Scanning Electron Microscope (SEM). The weight percentages of coir powder have significant effects on the mechanical properties of epoxy-coir-reinforced composites, such as tensile strength, impact energy, and toughness. Tensile qualities enhance along with 20 wt% coir powder loading, while impact energy and toughness increase with 30 wt% coir powder loading due to the powder's higher load-bearing capacity. Coir fibre composites treated with alkali (NaOH) have superior mechanical characteristics than untreated fibre composites. This procedure eliminates contaminants and harsher fibre surfaces, increasing the coir powder's adhesive ability in the composite matrix and resulting in improved mechanical qualities. Epoxy-Coir fibre reinforced composites have a possibility for application in low-cost housing [39], furniture [40], fencing, flooring [41,42], sports equipment [43], aerospace [44], and industrial applications [42]. These composites have a greater prospect for future development.

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