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Proceeding Paper

Mechanical, Moisture Absorption and Thermal Stability of Banana Fiber/Egg Shell Powder-Based Epoxy Composites †

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Abstract: This study aims to explore the viability of adding a hybrid blend of eggshell and banana fibers treated with NaOH to improve the structural characteristics of epoxy composites. In order to determine their appropriateness for different applications, the study includes assessments of mechanical performance, water permeability, and heat transfer properties. Chicken eggshell was used to make calcined eggshell particulate (CEP), and bananas were used to obtain processed banana fibers (TBF). For the creation of bio-composites, NaOH-treated banana fiber (30 wt.%) was integrated into an epoxy matrix with different weight percentages of CEP (like 0, 4, 8, 12, 16, and 20 wt.%) through the hand layup with a vacuum backing technique. Examination of the data revealed that, in comparison to epoxy with no reinforcement, the addition of bio-fillers improved the thermal insulation (4 wt.% of CEP exhibits 0.052 W/mk), water absorption (4 wt.% of CEP produced 5.31%), flexural strength (20 wt.% of CEP exhibit 36.57 MPa), and modulus (12 wt.% of CEP exhibit 300.12 MPa) of the hybrids. This suggests that by lowering the conductivity of the bio-based composites, the inclusion of these bio-based reinforcements improved their thermal insulation ability. The resistance to temperature fluctuations is stronger when there is less thermal conductivity.

Keywords: banana fiber; moisture absorption; thermal properties; egg shell powder; hybrid composites

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1. Introduction

In recent years, multiple initiatives have been launched to produce new creative and ecologically friendly substances for diverse purposes because of growing environmental and social consciousness. The exorbitant expense of synthetic fibers, as well as their negative effect on the environment, has spurred interest in natural fibers as a reinforcement for polymer composites [1]. In the modern generation of cutting-edge technologies, increasing the utilization of natural fiber-based hybrids provides potential environmental benefits by reducing reliance on hydrocarbon components. Natural fibers like cannabis, cotton, hemp, coco fiber, pineapple, mango, and papaya are renewable energies with little or no environmental impact because they are recyclable and biostable [2,3]. Because of their inherent environmental stewardship, they have an advantage over synthetic fabrics. For improving strength and productivity qualities, the remarkable mechanical capabilities of banana fiber related to its elevated cellulose content and small microfibril angles have already been considered. Moreover, banana fiber was selected for this research because of its accessibility, simplicity of separation, and light weight [4]. The interaction of NaOH with fiber during harsh chemical exposure is depicted in Equation (1) [5]. This procedure depletes the glucose in the fiber and allows short-length nanocrystals to form. The existence of NaOH in the situation requires the elimination of pectin, phenol, waxes, and lubricants that coat the external surfaces of cell membranes, enhancing surface quality and boosting carbon content on the surface of the composite. The oxidation reaction has been shown to have two impacts on fiber: Firstly, it enhances surface quality, resulting in improved adhesion strength. Secondly, it exposes more viscosity just on the surface of the fiber, resulting in a greater number of reactive species. Nevertheless, 5% NaOH-processed banana fiber-reinforced polyester materials outperformed 10% alkali-treated hybrids in regard to tensile strength. This is because at higher alkali concentrations, plant fibers break down too quickly, which leads to weak or broken fibers and a big drop in the tensile strength of the composite after a certain optimal NaOH level [6,7].

$$Fiber - OH + NaOH \rightarrow Fiber - O - Na + H_2O \quad (1)$$

Heat transfer in composites made with a polymer matrix is an important factor in quality control. The thermal performance of organic fiber composites with polymer matrices has received little research. As a result, research into the insulating characteristics of bio-filled polymer composites is required. For a number of reasons, it is critical to measure the thermal conductivity and moisture absorption behavior of natural fiber composites [8,9]:

- Material Characterization: It aids in comprehending the composite material's basic characteristics. These characteristics can have a big impact on how well and how long a material lasts in various applications.
- Performance Assessment: The composite's ability to transport heat is evaluated using thermal conductivity measurements. This is essential in areas where temperature control is important, such as the automotive, aerospace, or building sectors. Designing materials that absorb or release heat depending on the situation might benefit from understanding thermal conductivity.
- Moisture Management: Materials that will be exposed to humidity or moisture must exhibit certain behaviors when it comes to absorbing moisture. It may affect the material's overall performance, dimensional stability, and mechanical qualities. Controlling moisture absorption is crucial for durability in applications such as outdoor construction, maritime, or transportation.
- Quality Control: Manufacturers can develop quality control criteria to guarantee consistent and dependable material performance by measuring these attributes. This is crucial in businesses where dependable products are essential.
- Design Optimizations: Engineers and designers may optimize the composite material for particular applications by understanding heat conductivity and moisture retention behavior. They can modify the material's structure and composition to match the needs of a certain environment or use case.

In conclusion, it is critical to measure the thermal conductivity and moisture absorption behavior of natural fiber composites in order to ensure their suitability, performance, and durability in a variety of applications. It is also important to optimize their design and encourage the use of these materials in environmentally friendly and cost-effective solutions. The uniqueness of this work comes from its thorough examination of the varied characteristics of epoxy composites made from eggshell powder and banana fiber, where the synergistic impacts of these environmentally friendly and renewable resources are investigated. This study not only adds to the growing body of research on composite substances, but it also provides insightful information about possible uses for these materials, particularly in industries where mechanical strength, moisture resistance, and thermal stability are critical factors, encouraging advancements in environmentally friendly material science. This research demonstrates the inherent potentials of combining animal and plant reinforcement rather than employing them individually in the traditional manner.

2. Experimental Works

2.1. Materials

Resources like epoxy resin and its hardener used in this study were purchased from CVR Enterprises, Bangalore, Karnataka, India, while banana fiber was collected from a local location in Tamil Nadu, India. CVR Pharmaceuticals supplied analytical-grade NaOH, while comparable firms in India supplied epoxy resins and curing agents.

2.2. Composite Fabrication

In the current study, hybrid composite materials were created using a hand layup technique combined with vacuum backing. To get rid of air and extra resin, the mat made of natural banana fiber was placed in a vacuum bag. After that, the eggshell powder and resin mixture were added to the bag and allowed to penetrate the mat while under vacuum (15 bar). Through this method, eggshell powder was infused with the fiber mat. The eggshell grains and banana fiber were mixed into the epoxy in amounts ranging from 4 to 20 percent by weight to create the bio-based hybrids. The epoxy resin and curing agent were mixed in a 2:1 ratio. For every lab test, a homogenous combination of epoxy coating, curing agent, and CEP/TBF was created by continuously stirring the mixture in a plastic bottle for 2 min with a fiberglass rod. The compound solutions were then placed into molds tailored for every attribute to be tested and allowed to dry in the air at a room temperature of 24 °C before being withdrawn. Without such supports, a reference specimen was developed using only epoxy and curing agents. Following that, the completed specimens were examined in accordance with ASTM requirements. Figure 1 shows schematic representations of hybrid composite fabrication methods.

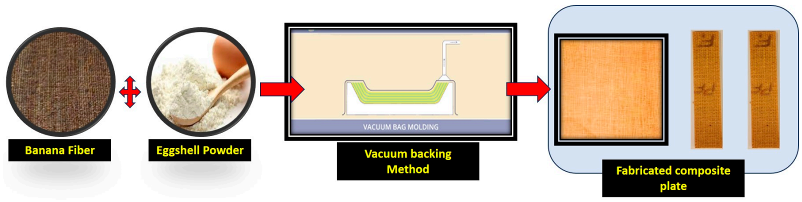

Figure 1. Schematic representation of composite fabrication process.

2.3. Material Characterization

The materials' bending properties were evaluated using a three-point bending test. The bending examination was carried out using a Universal Testing Apparatus Series 3369 version in line with the ASTM D790-03 (2003) standards [10]. A specimen cut into 125 × 12.7 × 3 mm was put in the machine's grasp and stretched to a span of more than 40 mm at a testing velocity of 5 mm per minute [11]. Microstructural analysis of the fractured specimen was carried out using a scanning electron microscope (SEM). The heat transfer of the produced composites was determined to be achieved using Lee's disc device in compliance with ASTM E1530-19 (2019) [12]. A thermal performance examination was performed at temperatures ranging from 50 °C to 80 °C, and no thermal or heat deterioration was seen since it was not evaluated at a temperature near the triggering of deterioration. Water uptake testing was performed in line with ASTM D5229M-12 (2012) [13]. An amount of 250 cm^3 of aquatic media was put into cleaned plastic tubs for the experiment.

3. Results and Discussion

3.1. Flexural Strength

The bending test results reveal an increase in the bending strength of composites that ranges from 4 to 20 weight percent, as shown in Figure 2. Flexural strength is increased as the fraction of CEP-TSF rises; thus, the combination comprising 20% wt.% CEP-TBF has a maximum bending strength of 36.57 MPa. According to Figure 2, the elastic strength of the composites increases when the CEP-TBF rises from 4 to 12 wt.% and then decreases from

12 to 20 wt.%. On the other hand, the decline in flexural from 12 to 20 wt% was modest and negligible when contrasted to the impact of 4–8 wt% well before formulation with an ideal value. As a result, the bending elasticity rises in relation to the CEP-TBF percentage [14].

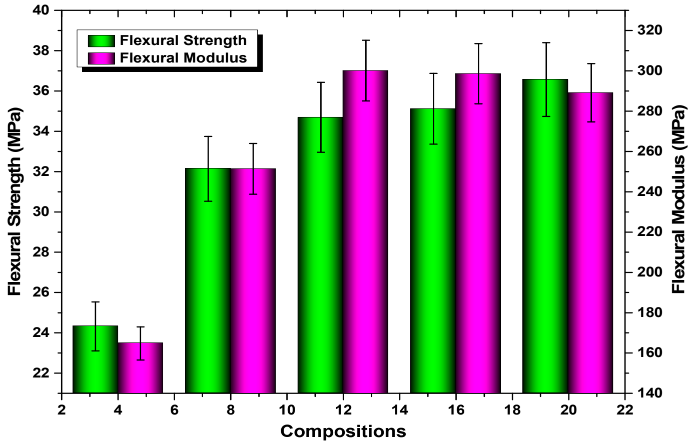

Figure 2. Flexural strength and modulus of NaOH-treated banana/CEP-based hybrid composites with different composition of filler.

The specimen containing 12 wt% CEP-TBF had a maximum elastic strength of 300.12 MPa. The specimen with 4 wt% CEP-TBF bio-filler did not improve in either property. This means that the bending properties can only be improved by adding 8–16 wt% CEP-TBF bio-filler. According to the findings, the improvements in bending rigidity and modulus were 33% and 71%, respectively. As a result, the CEP gets tougher and more rigid, allowing for superior flex qualities in combination with processed banana fiber, which is robust and rigid [14]. This is the main reason for the hybrid's development in such mixtures, wherein differing characteristics of the two primary reinforcing components are predicted. The conclusion of the cooperation in this situation was positive, and it bodes well for future study.

3.2. Thermal Conductivity

Figure 3 depicts the fluctuation in heat capacity in epoxy matrix bio-composites with increased CEP-TBF. The produced materials have a lower heat conductance than the reference group. This means that the inclusion of these bio-based reinforcements improved the heat insulation characteristics of the organic polymers by lowering their permeability. Poor thermal conduction suggests greater tolerance to heat fluctuations. Among the bio-composites created, the specimen with 4 wt.% CEP-TBF had the lowest heat capacity, with a value of 0.05107 W/mK. The heat transfer of the created bio-composites increased as the CEP-TBF increased, but none was higher than the sample group. As a result, the inclusion of this bio-fiber increased the insulation qualities of the bio-composites created. This conclusion was consistent with the findings of Alshahrani [15], who showed that the addition of banana fiber to epoxy improved the insulating efficiency of composite materials, both chemically modified and unmodified fiber-reinforced materials. Many researchers found that hemp and abaca fibers increased the insulating qualities of polyamide as well as the wall components. As a result, whenever the sample with the lowest heat capacity was paired with the control sample, a 43% insulation increase was obtained. As CEP filler concentrations improved in the current study, the hybrid composite's thermal conductivity also improved. This may occur because additional filler will improve the composite's total thermal conductivity if the filler material has a greater thermal conductivity than the matrix material [16]. This is due to the highly conductive filler having a greater impact on the heat transmission within the composite. Within the composite, filler particle placement and distribution are extremely important. To maximize the improvement in heat conductivity, the filler particles should be evenly distributed throughout the matrix. It is critical to consider how well the filler and matrix interface. An effective thermal coupling or strong link between the two can help with heat transmission. A weak contact or inadequate adhesion may prevent an increase in heat conductivity [17].

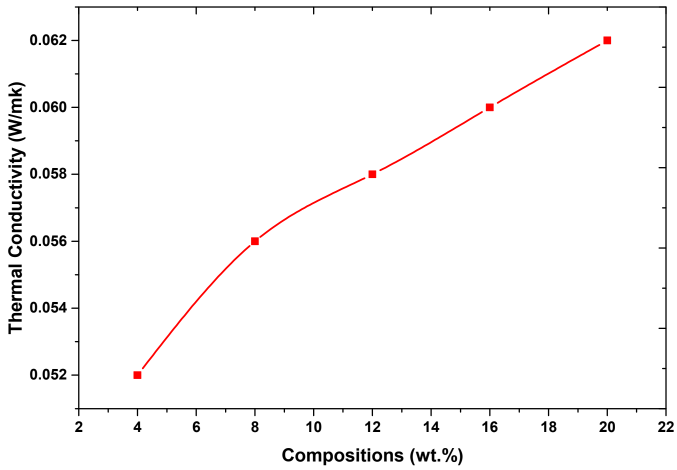

Figure 3. Thermal conductivity of NaOH-treated banana/CEP-based hybrid composites with different compositions of filler.

3.3. Moisture Absorption

Figure 4a,b demonstrate how the water uptake characteristics of strengthened epoxy composites changed with the introduction of CEP-TBF. Figure 4a depicts the materials' response when revealed in a water phase throughout time. The mass obtained by reference or composite specimens rises over time, as found. The mass obtained by preparing specimens grows from 4 to 20% wt.% as the great extent percentage rises. The chart illustrates that all of the specimens contain moisture quickly and steadily from the beginning until reaching saturation at 110 h, with no further rise in water uptake observed over 160 h. The diffusion was quick and straight from 0 to 24 h, whereas the rate of water absorption was moderate and constant from 24 to 110 h. During the next 110 to 160 h, the behavior indicated a flat and saturated state [18]. According to Fick's law, the first step is Scenario I (Fick's dispersion, n = 0.5), where polymeric relaxation is significantly quicker than diffusion of water, and the dispersion is accompanied by an immediate reaction of the environment, culminating in Fick's behavior.

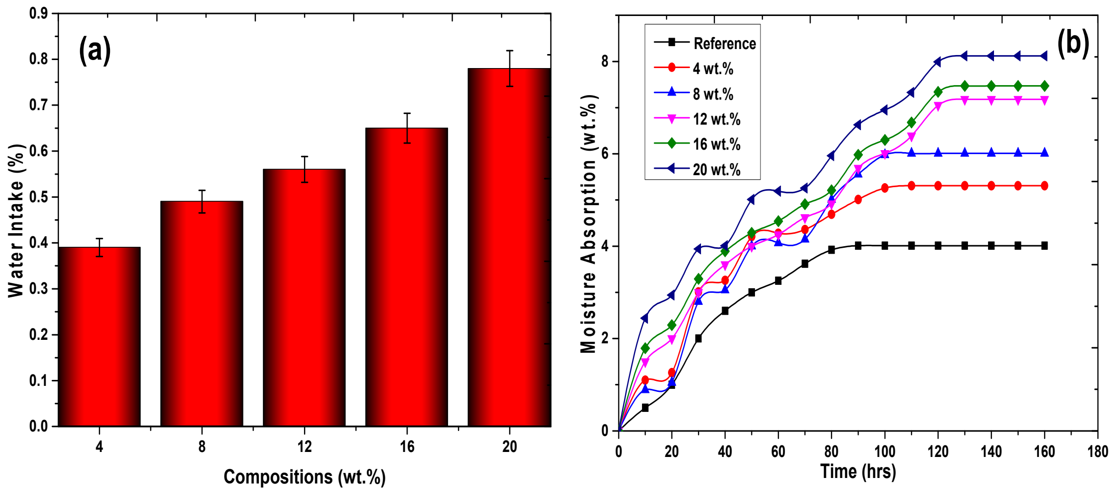

Figure 4. (**a**) Overall absorption rate; (**b**) water absorption potential of composite at different hrs.

The system's immediate responsiveness necessitates a significant amount of pliability in the polymer, i.e., the polymer is in a stretchy condition. This has been accompanied by a diffusion rate that is equivalent to the rate of relaxation (anomalous dissemination, n > 1), wherein the development of Mega Scenario II renders it somewhat dubious in certain conditions. As a result, there has been a prolonged and erratic method of dispersion over this time period [19]. The third phase, which lasted from 110 to 160 h, demonstrated that the dispersion of transpiration of water remains consistent or set, so this is known as the critical mass, which further occurs in a short amount of time. Figure 4b depicts the water uptake percentage of the specimens at the conclusion of the soaking time (160 h). After 160 h, the overall water acquisition, even in a controlled experiment, was 0.29%, whereas the combination with the least water uptake was 4 wt%. The CEP-TBF strengthened the bio composite with a figure of roughly 0.41%. According to the conclusions, the main results are explained by the existence of hydrophobic bio-fiber (bananas), which results in increased water absorption. A high proportion of water uptake in specimens causes composites to expand, implying the possibility of brittle fracture. As a result, a low proportion of water uptake is preferred to limit or avoid crack propagation [20].

3.4. Microstructural Examination

Figure 5 shows the shattered surfaces of samples that performed best across a range of characteristics, giving important insights into the microstructure of the created bio-composites. Figure 5a shows well-dispersed 4 weight percent CEP-TBF in the epoxy matrix with little pore development. The structural design of the composite supports its excellent characteristics for thermal insulation and water resistance. Figure 5b, which similarly shows evenly scattered reinforcements, depicts the fracture image of the 16 wt.% CEP-TBF-reinforced epoxy matrix. The fiber–matrix interface of this sample, however, exhibits additional characteristics such as porosity, fiber pull-out, and debonding [21]. These factors suggest a worse stress and load transmission mechanism during the formation of polymer composites, which explains why the majority of mechanical characteristics did not considerably increase in comparison to other compositions. However, this specific sample shows little advantage in peak flexural strength. The outcomes of the mechanical tests support the creation of hybrid bio-composites that successfully address the deficiencies of the epoxy matrix by integrating sisal fiber and eggshell particles. The composites also exhibit higher moisture resistance and enhanced insulation properties [22].

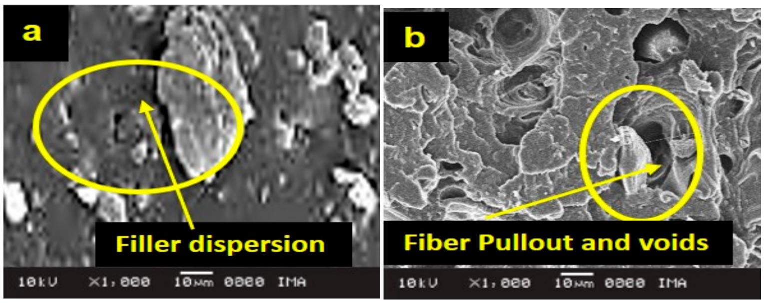

Figure 5. SEM image of banana-based hybrid epoxy composites (**a**) 4 wt.% of ESP filler; (**b**) 16 wt.% of ESP filler after flexural testing.

4. Conclusions

The investigation of the mechanical, moisture absorption, and thermal stability of epoxy composites made from banana fiber and eggshell powder has shed important light on the possibility of using these bio-composite materials for a variety of purposes.

- Mechanically, adding eggshell powder to the composite has shown promise, improving the materials' flexural strength (36.57 MPa) and their modulus (300.12 MPa). This shows that these composites may be exploited as structural elements in a variety of sectors, utilizing the beneficial interactions between banana fibers and eggshell granules.

- The study found that when the concentration of CEP filler increased, along with natural banana fiber, it exhibited good thermal and increased water uptake properties. Because poor thermal conductivity suggests strong insulation and low water absorption indicates resistance to water retention, samples with 4% weight of CEP-TBF performed best in terms of insulation and water resistance.

5. Potential Applications of Present Research

The findings from the study on the composite material comprising CEP filler and natural banana fiber have several potential real-time applications:

- Insulation Materials: The 4% weight of CEP-TBF in the composite material, which shows strong thermal insulation capabilities, can be used in the building sector. Buildings can use it as insulation to increase energy efficiency and lessen heat transmission.
- Moisture-Resistant Components: The composite is appropriate for applications where moisture resistance is essential due to its resistance to water retention, particularly at greater weight fractions. It might be used, for instance, in outdoor furniture, marine parts, or any other application exposed to moist or humid situations.
- Structural Components: These composites may be employed as structural components in a variety of sectors, including automotive, aerospace, and construction, based on the reported improvement in flexural properties at weight fractions between 8 and 20%. They can offer both strength and durability.
- Packaging: In packing applications, composite products that withstand moisture can be employed, notably for goods that must stay dry throughout travel and storage. Food packaging, medical wrapping, and electronic containers are some examples of this.

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