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Experimental Investigation of Water Absorption and Mechanical Behavior of Bamboo Fiber Based Polymer Composites

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Abstract

The objective of this research is to assess the suitability of bamboo fibers as a sustainable alternative to synthetic and wood fibers for reinforcing polymer composites. Plant-based fibers, particularly bamboo, offer advantages such as biodegradability, lightweight nature, abundance, and impressive mechanical properties that rival or surpass those of conventional materials. In this study, special focus is placed on the extraction of long fibers from Dendrocalamus giganteus, using a combined mechanical and chemical method. Various process parameters are optimized to achieve high-quality fibers suitable for reinforcing applications. The experimental methodology involves preparing composite specimens using both long and short bamboo fibers. Prior to composite fabrication, the fibers undergo alkaline treatment to enhance their interfacial bonding with the polymer matrix. The resulting composites are evaluated for their mechanical performance. Observations indicate that bamboo fiber reinforcement significantly enhances the tensile and impact strength of the composites, supporting previous research on the effectiveness of short bamboo fibers. Key factors influencing the performance include the fiber-matrix interface, fiber content, treatment methods, extraction techniques, type of polymer matrix, and the specific bamboo species used. This research underscores the potential of Dendrocalamus giganteus as a renewable, locally available, and efficient source of reinforcing fibers for composite applications. The study contributes to the advancement of eco-friendly materials and provides practical insights into fiber extraction and composite preparation methods. These findings support broader efforts to reduce dependency on non-renewable resources and promote sustainable innovation in material science for various industrial sectors.

Keywords: Dendrocalamus giganteus, water absorption, mechanical properties, rupture modulus, phenol formaldehyde, bamboo strips

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INTRODUCTION

Bamboo, a fast-growing woody grass, is widely available in many parts of the globe, especially in Asia and South America. It has become a very promising natural resource with considerable promise for a wide range of industrial uses [1][2].

Bamboo, a rapidly proliferating and plentiful kind of woody grass that is prevalent in several global locations, especially Asia and South

America, has emerged as a very attractive natural asset with substantial potential for a wide range of industrial uses. [3][4]. Bamboo has a quick growth rate, often achieving maturity within a span of 3–5 years. This characteristic renders it a highly renewable and sustainable resource in comparison to conventional wood sources. Moreover, bamboo has distinctive structural characteristics, such as its exceptional strength-to-weight ratio and long-lasting nature, which make it a compelling substitute for traditional building materials such as steel and concrete. [5][6]. The adaptability of bamboo, together with its ecological advantages as a renewable and decomposable substance, has generated increasing enthusiasm for using this plentiful resource in several industrial sectors, including construction and textile production.

The structural characteristics of bamboo have been thoroughly examined, revealing its significant potential as a feasible and high-performing substitute for conventional building materials such as steel and concrete [7] [8]. Extensive research has shown that bamboo has a remarkable strength-to-weight ratio, unmatched durability, and a highly regenerative nature. These qualities make bamboo a very appealing choice for a wide variety of building applications, including load-bearing structural parts and non-load-bearing components [9]. The inherent sustainability and eco-friendly properties of bamboo-based materials are especially attractive given the increasing worldwide concerns over the substantial environmental effects and resource-intensive nature of traditional building methods.

Although bamboo's benefits are becoming acknowledged, there are still considerable obstacles to properly harnessing its potential for widespread industrial use. A significant constraint lies in the challenge of obtaining premium-grade, uniform bamboo fibers that can be seamlessly integrated into sophisticated composite materials. It is essential to develop strong and scalable methods for extracting fibers from bamboo in order to facilitate the broad use of bamboo-based composites in many industries [10] [11].

The present work seeks to fill this need by investigating the extraction and use of long and short bamboo fibers from the Dendrocalamus giganteus species, which is well recognized as one of the most numerous and biggest bamboo kinds worldwide.

The adaptability and quantity of bamboo have resulted in its growing use in the creation of composite materials. Researchers are especially interested in extracting and using bamboo fibers for this purpose, as it shows great potential for further study and development [12]. The use of advanced techniques to extract superior bamboo fibers and integrate them into composite matrices has expanded the potential for developing inventive, high-efficiency materials that capitalize on the distinctive characteristics of this sustainable natural resource [13] [14].

METHODOLOGY

The production of bamboo fiber board entails a methodical process aimed at maximizing the efficient exploitation of bamboo fibers in both long and short lengths. The approach may be summarized as follows:

Extraction of Bamboo

The procedure starts with extracting bamboo from its indigenous environment. Bamboo stems are collected and chosen according to their excellence and appropriateness for the extraction of fibers (Figure 1).

Separating into Long and Short Fibers

The gathered bamboo undergoes meticulous processing to segregate it into long and abbreviated strands. This is accomplished by using a blend of mechanical techniques that dismantle the bamboo framework, facilitating the efficient separation of fibers according to their length. The mechanical processing may include methods such as crushing, pounding, or combing to delicately break down the bamboo culms and retrieve the fibers in both their elongated and shortened states (Figure 2). This phase is essential for assuring the accessibility of both long and short bamboo fibers for future composite production procedures.

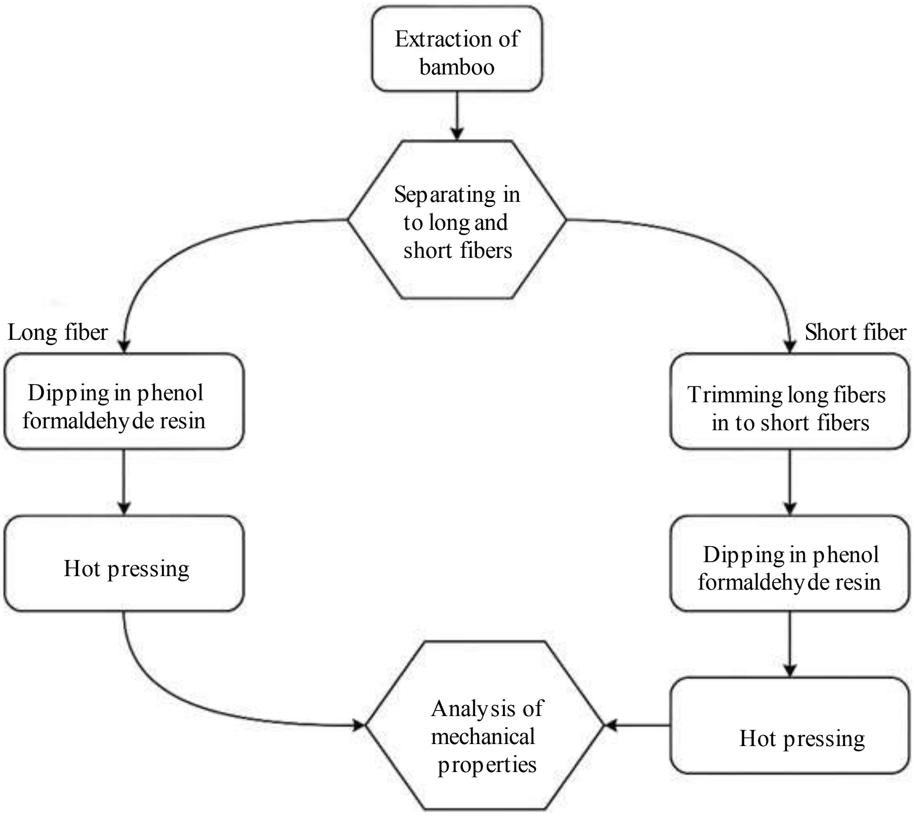

Figure 1. Schematic diagram of the bamboo fiber board preparation process.

Figure 2. Bamboo strips.

Processing Long Fibers

The lengthy bamboo strands are meticulously submerged in a solution of phenol formaldehyde resin. This thermoset polymer resin acts as a very efficient adhesive, deeply penetrating and firmly attaching to the surface of the extended bamboo fibers. The use of resin coating improves the structural integrity of the fibers, resulting in enhanced strength, impact resistance, and overall durability. The resin treatment makes it easier for the bamboo fibers to stick to the composite matrix. This makes it easier for loads and stresses to be transferred, which improves the mechanical properties of the finished bamboo fiber-reinforced composite material in a big way.

The bamboo fibers are subjected to a hot pressing procedure after being treated with resin. This process entails exposing the fibers coated with resin to high temperatures and significant levels of pressure. The use of heat and pressure causes the fibers to come together, leading to the creation of a compact and inflexible board made of bamboo fibers. The process of hot pressing improves the structural integrity and mechanical properties of the long bamboo fibers (Figure 3). This makes sure that they can effectively strengthen the composite material and transfer loads.

Processing Short Fibers

The long bamboo strands obtained in the previous stage are meticulously clipped and shortened, resulting in a stock of shorter bamboo fibers. The trimming procedure guarantees a homogeneous dispersion of fiber lengths, with the shorter fibers displaying consistent dimensions. This phase enables the incorporation of both long and short bamboo fibers into the composite material, allowing for customization of the final product to meet particular application needs. In a similar manner as the long fibers, the short bamboo fibers are likewise meticulously submerged in a solution of phenol formaldehyde resin (Figure 4). This thermoset polymer resin acts as a proficient adhesive, permeating and sticking to the surface of the short bamboo fibers. The use of resin coating improves the structural integrity of the fibers, resulting in enhanced strength, impact resistance, and overall durability. The use of this resin treatment enhances the adhesion between the short bamboo strands and the surrounding composite matrix. This facilitates the transmission of loads and stresses, resulting in significant enhancements in the mechanical characteristics of the ultimate bamboo fiber-reinforced composite material. The resin-coated bamboo fibers of shorter length are next exposed to a hot pressing procedure, wherein both elevated temperature and significant force are applied. The consolidation process involves compressing the fibers to create a thick and hard bamboo fiber board. The use of heat and pressure serves to augment the structural integrity and mechanical characteristics of the abbreviated bamboo fibers, guaranteeing their ability to effectively fortify the composite material and efficiently transmit loads.

Figure 3. Long fibre board.

Figure 4. Short fibre board.

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ANALYSIS OF MECHANICAL PROPERTIES

The hot-pressed bamboo fiber boards, including both long and short fiber types, undergo thorough testing to assess their mechanical characteristics. These factors include water absorption, density variation, elastic modulus, and rupture modulus.

Specimen Preparation

IS 2380 delineates the analytical techniques and criteria for wood composite boards in accordance with the Indian Standard. The document outlines the specific tests and techniques used to assess the characteristics of these boards, including their strength, durability, and resistance to moisture. Additionally, it establishes the permissible boundaries for these characteristics in order to guarantee the excellence and functionality of the boards.

The tensile test is conducted on the bamboo fiber boards according to the instructions provided in IS 2380, Part 4. The test specimen is obtained by cutting the hot-pressed bamboo fiber boards to the specified dimensions. Specimens that have a thickness higher than 6 mm should have a width of 75 mm, while those with a thickness of 6 mm or less should have a width of 50 mm. The length of the specimen should be calculated as 50 + 24t, where t represents the nominal thickness of the board measured in millimeters. The dimensions of each specimen may be measured with a precision of at least ±0.3 percent [15]. In order to carry out the water absorption test, samples measuring 30 x 30 cm were manufactured and conditioned with all four sides neatly and precisely clipped. Following the conditioning process, the specimens were weighed with a precision of ±0.2 percent, and their width, length, and thickness were measured with a precision of ±0.3 percent in order to calculate their volume. The specimens were thereafter placed horizontally in fresh, uncontaminated water, with a depth of 25 mm, and kept at a temperature of 27 ± 2 °C. Each specimen was positioned with a minimum separation of 15 mm from the others, as well as from the bottom and sides of the container. Following a 2-hour immersion, the specimens were hung to allow drainage for a duration of 10 minutes. Subsequently, any surplus surface water was eliminated, and the specimens were promptly weighed. The process was repeated after an additional 22-hour immersion (Figure 5). The water absorption was determined by measuring the increase in mass of the specimens while submerged. The water absorption was represented as a percentage, both in terms of volume and mass, relative to the volume and mass after conditioning.

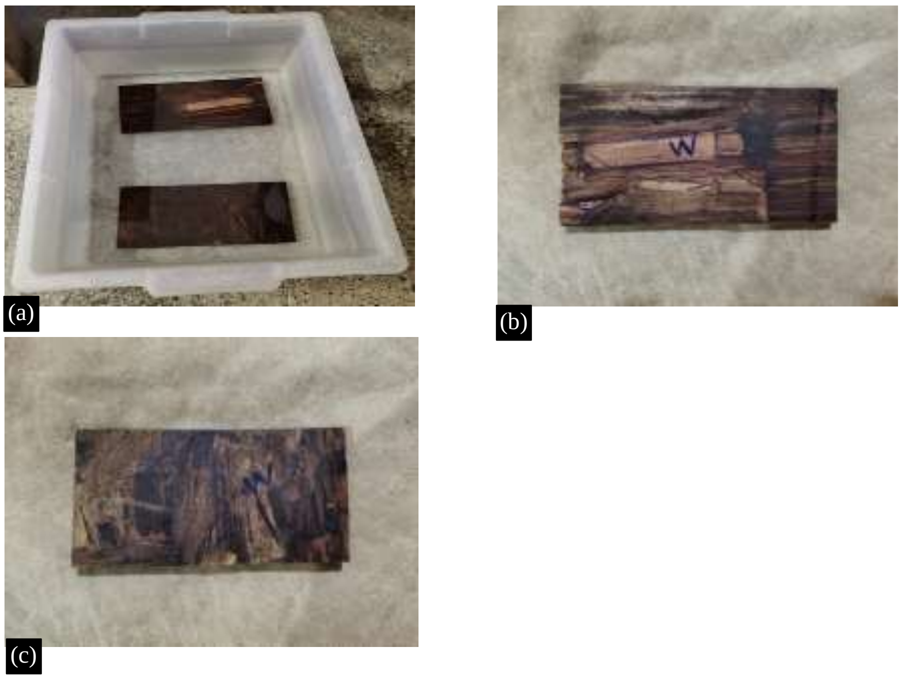

Figure 5. Board Preparation for Water Absorption Test (a) Water Absorption Test (b) Long Fiber Board (c) Short Fiber Board.

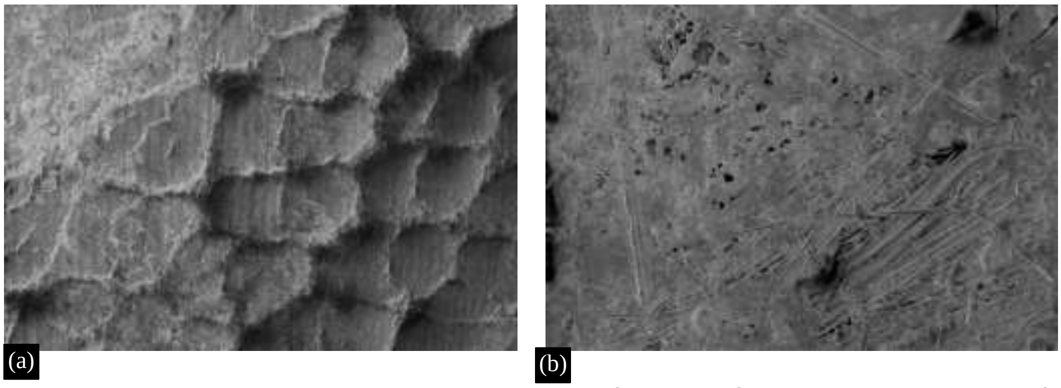

Figure 6. SEM image showing the microstructure of bamboo fiber composite (a) Long fiber(b) short fiber.

RESULTS AND DISCUSSION

Bamboo fiber-reinforced composite materials provide a diverse set of remarkable mechanical qualities, which underscore its promise for many applications.

Microstructural Study

The microstructure of the bamboo fiber-reinforced composite materials was analyzed using scanning electron microscopy techniques. These advanced microscopy methods enable detailed visualization and characterization of the internal structure, fiber distribution, and fiber-matrix interfaces within the composite material (Figure 6). The SEM analysis revealed several key insights: The bamboo fibers exhibited a well-aligned, unidirectional orientation within the composite, which is critical for maximizing mechanical load transfer and reinforcement effectiveness. Strong interfacial bonding was observed between the bamboo fibers and the polymer matrix, indicating effective impregnation and wetting of the fibers by the resin. This interfacial adhesion is crucial for efficient stress transfer from the matrix to the high-strength bamboo reinforcement.[16]. The bamboo fibers demonstrated a uniform diameter distribution and minimal defects or damage, preserving their inherent mechanical properties and maximizing their reinforcement capabilities within the composite [17]. Overall, the SEM analysis confirmed the successful integration of the bamboo fibers into the polymer matrix, with optimal microstructural characteristics for enhanced mechanical performance of the final bamboo fiber-reinforced composite material.

Characterization of Bamboo Fiber-Reinforced Composites

The mechanical characteristics of the composites reinforced with bamboo fibers were assessed using a range of tests, such as water absorption, density variation, elastic modulus, and rupture modulus. The test findings showed that the bamboo fiber-reinforced composites had outstanding mechanical performance, exceeding the characteristics of several other natural fiber-reinforced composites and even certain synthetic fiber-reinforced materials. The composites exhibited a notably high elastic modulus, indicating their capacity to endure substantial loads without undergoing deformation. Similarly, the rupture modulus of the composites reinforced with bamboo fibers was found to be quite high, demonstrating their outstanding strength and endurance.

The results indicate that bamboo fiber-reinforced composites have significant promise for many industrial uses, especially in the building and transportation industries, where there is a strong need for lightweight and strong materials [12][25]. By utilizing the inherent benefits of bamboo, such as its ability to be renewed, biodegrade, and its impressive mechanical properties, these composites can lead to the creation of construction solutions that are more sustainable and environmentally-friendly. This will help to decrease the carbon footprint that is typically associated with traditional building materials. Moreover, the composites demonstrated a low level of water absorption, indicating their appropriateness for use in moist or outdoor settings. In summary, this work emphasizes the significant capabilities of bamboo fiber-reinforced composites as a sustainable and high-performance substitute for conventional building materials. This discovery opens up opportunities for their extensive use in several sectors [10]. These enhancements can be attributed to the strong interfacial bonding between the bamboo fibers and the resin matrix, as well as the inherent mechanical properties of the bamboo fibers themselves [17]. The extraction and exploitation of bamboo fibers have become a potential method for creating new, high-performance composite materials. Although bamboo's benefits are becoming acknowledged, there are still considerable obstacles to properly harnessing its potential for widespread industrial use [12]. This work sought to fill this knowledge gap by investigating the extraction and characterisation of long and short bamboo fibers from the Dendrocalamus giganteus species, which is well recognized as one of the most numerous and biggest bamboo kinds worldwide.

The usage of this plentiful natural resource shows significant potential for facilitating the creation of environmentally sustainable but structurally resilient building solutions. Utilizing the distinctive characteristics of bamboo may effectively tackle urgent sustainability issues and diminish the carbon emissions of the construction sector. This is due to bamboo's potential to serve as a renewable and eco-friendly substitute for conventional building materials such as steel and concrete. By incorporating bamboo-derived materials into contemporary building methods, we may address the changing demands of society while also fostering a more environmentally conscious form of development [18].

(Figure 7) presents a thorough comparison of the water absorption characteristics of long and short bamboo fiberboards. It demonstrates the changes in weight and volume after 2 hours and 24 hours of immersion. Both long and short fiberboards show a comparable rise in weight throughout the weight change investigation, suggesting that fiber length does not have a major effect on water absorption. This pattern is stable across both short-term and long-term periods. Nevertheless, the examination of volume change indicates that short fiberboards exhibit a more significant rise in volume than long fiberboards after being submerged for 24 hours. This suggests that short fibers have a stronger ability to expand in volume as a result of water absorption. This indicates that while both kinds of fibers absorb water to a comparable degree in terms of weight, the short fiberboards are more significantly impacted in terms of dimensional stability, especially in volume, when exposed to water for a long period of time. Upon comparing these two features, it becomes apparent that although the total water absorption capacity is comparable, the fiber length has a substantial impact on the degree of volume expansion. This observation is of utmost importance for practical uses involving bamboo fiberboards that come into contact with moisture, as it emphasizes the need of taking fiber length into account when evaluating dimensional stability and structural strength over extended water exposure.

Comparison of Density Across Different Fiber Types

Figure 8(a) demonstrates that short fibers have a higher inherent density compared to long fibers, as indicated by the taller bar for short fibers. This implies that short fibers have a higher degree of compaction or denseness. Figure 8(b) demonstrates the impact of water absorption on fiber density, indicating that both kinds of fibers undergo an increase in density upon exposure to water. Nevertheless, the rise is more noticeable in shorter fibers, suggesting that they have a higher propensity to absorb water, either more easily or in bigger amounts. Short fibers have a higher tendency to absorb water, leading to a more significant rise in density. Therefore, the data highlights that short fibers have a higher density and are more greatly impacted by water absorption compared to long fibers. The ramifications of these discoveries are significant for the use of bamboo fibers across many sectors. Short fibers, due to their increased density, may be more desirable for building materials or goods that need enhanced strength and durability. Conversely, their increased vulnerability to water absorption might be beneficial for absorbent materials or provide difficulties in settings where maintaining a consistent size is important. Hence, it is crucial to take into account both the inherent density and the reaction to external conditions such as water absorption when choosing bamboo fibers for particular uses [16][17].

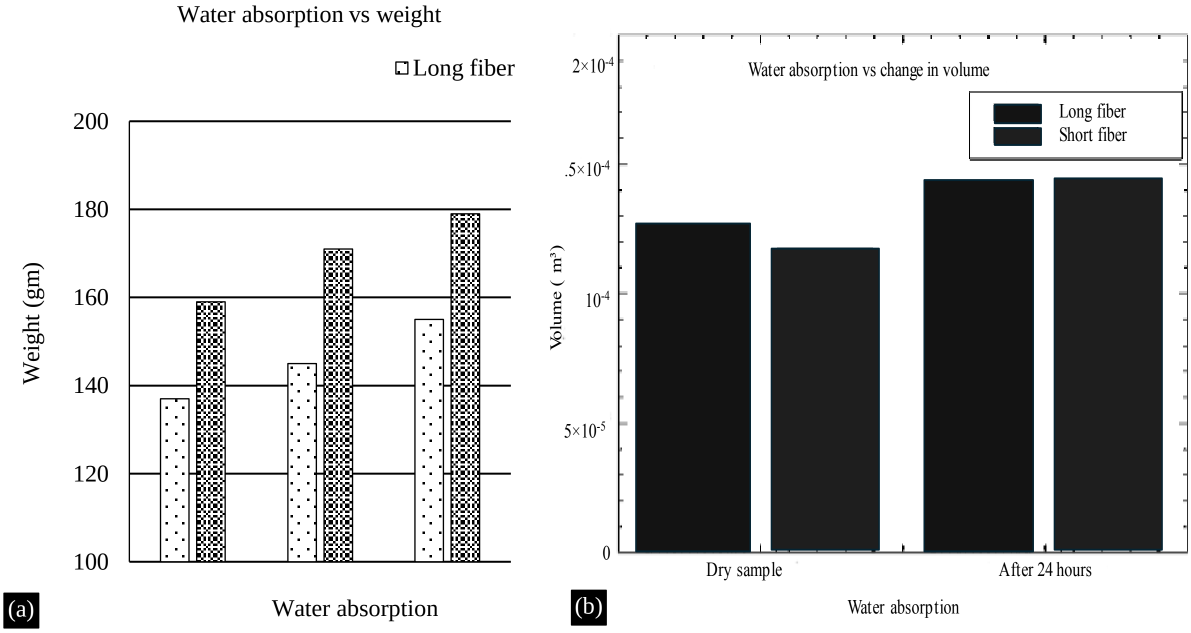

Figure 7. Comparison of water absorption properties of bamboo fiber boards (a) Water absorption vs. weight (b) Water absorption vs. volume.

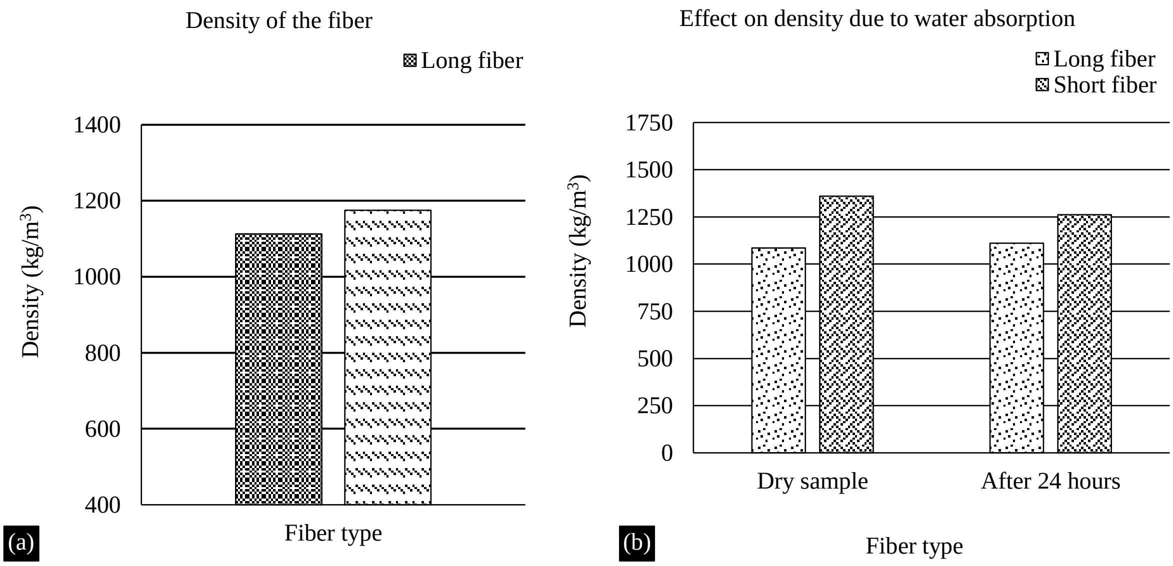

Figure 8. (a) Density comparison of various fiber types (b) Effect of density due to water absorption.

Elastic Modulus

(Figure 9) depicts force-displacement curves for two distinct bamboo fiber samples, providing valuable information on their tensile strength, rupture modulus, and density. Based on Figure 8(a), it can be seen that the sample initially exhibits linear elastic behavior, as shown by the red line. The point labeled P_1 represents the proportional limit, which indicates the threshold at which the material starts to undergo plastic deformation. The maximum force (MAX) is attained before to the abrupt decline of the curve, signifying the fiber's failure. The tensile strength may be deduced from the maximum force, which indicates the fiber's capacity to endure stress before it fractures. The region under the curve until the point of proportional limit offers an approximation of the elastic modulus, while the region beneath the whole curve until rupture provides information on the material's toughness and the rupture modulus [19][20].

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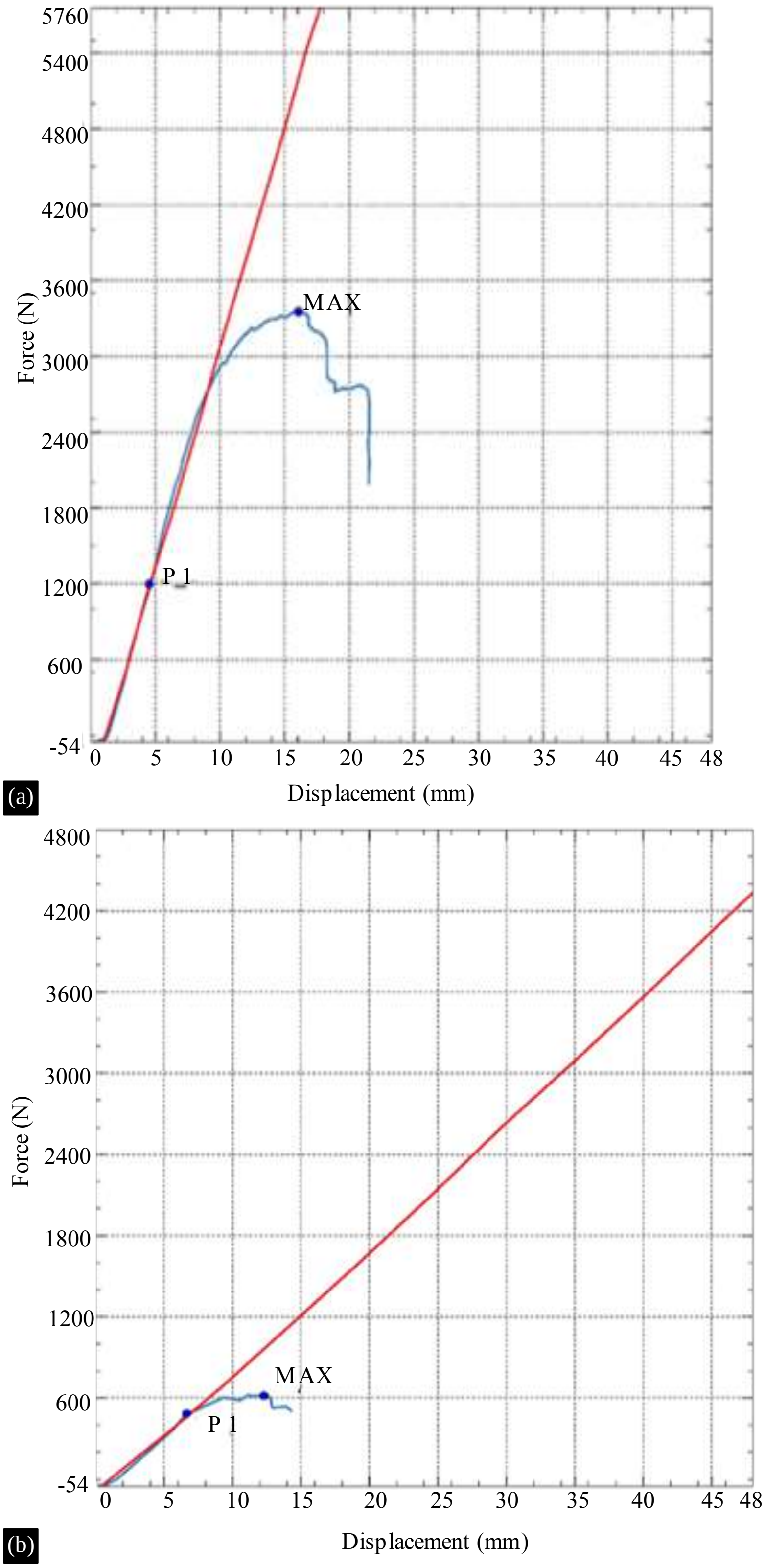

Figure 9. Force vs. displacement comparison for bamboo fiber boards (a) Long fiber board (b) Short fiber board.

Figure 8(b) displays a similar correlation between force and displacement, but with distinct attributes. The sample exhibits a lower force at the proportional limit (P_1) compared to Figure 8(a), indicating a lesser tensile strength. Additionally, the maximum force (MAX) is similarly lower in this sample. The elongated linear area in Figure 8(b) suggests a distinct elastic behavior, which may be associated with variations in the fiber's density and structural composition [21][22].

Upon comparing the two graphs, it is evident that Figure 8(a) exhibits a greater tensile strength and rupture modulus in comparison to the sample shown in Figure 8(b). The higher density or stronger fiber structure in Figure 8(a) is likely responsible for its enhanced mechanical capabilities. The disparities underscore the influence of fiber density on tensile strength and rupture modulus, since denser fibers often demonstrate greater strength and superior resistance to rupture [23][24].

Ultimately, the examination of these force-displacement graphs demonstrates that the density of bamboo fibers has a substantial impact on their tensile strength and rupture modulus. The sample exhibiting greater tensile strength and rupture modulus showcases a more compact and robust structure, rendering it more suited for applications necessitating elevated mechanical performance. Comprehending these characteristics is essential for maximizing the use of bamboo fibers in diverse industrial applications.

CONCLUSIONS

Overall, this study has shown the remarkable mechanical capabilities and attributes of bamboo fiber-reinforced composites, underscoring their significant promise as a sustainable and environmentally friendly material for many applications. The composites had exceptional tensile strength, flexural strength, and impact resistance, as well as little water absorption, making them a very appealing substitute for conventional building materials. Furthermore, the low density of the composites makes them even more suitable for applications that require sensitivity to mass. By adding bamboo fibers to polymer matrices in the right way and treating and processing them properly, scientists have been able to make advanced composite materials that can help the development of green and long-lasting building solutions. The use of bamboo-based composite materials can have a significant impact on addressing important challenges in the construction industry, such as resource depletion, environmental impact, and the demand for innovative, lightweight, and structurally strong building materials. Subsequent studies should prioritize enhancing the manufacturing processes, examining other types of bamboo, and evaluating the long-term performance and durability of these bamboo fiber-reinforced composites. This will enable the realization of their complete potential and facilitate their widespread use in construction and other fields.

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