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Physico-Mechanical Property Evaluation and Morphology Study of Moisture-Treated Hemp–Banana Natural-Fiber-Reinforced Green Composites

Ravi Yerraiahgarahalli Venkataravanappa [1], Avinash Lakshmikanthan [2,*], Natesan Kapilan [2], Manjunath Patel Gowdru Chandrashekarappa [3,*], Oguzhan Der [4] and Ali Ercetin [5]

[1] Department of Mechanical Engineering, Nagarjuna College of Engineering & Technology, Visvesvaraya Technological University, Belagavi 590018, India; raviyv@ncetmail.com
[2] Department of Mechanical Engineering, Nitte Meenakshi Institute of Technology, Visvesvaraya Technological University, Belagavi 590018, India; kapilan.n@nmit.ac.in
[3] Department of Mechanical Engineering, PES Institute of Technology and Management, Visvesvaraya Technological University, Belagavi 590018, India
[4] Department of Marine Vehicles Management Engineering, Maritime Faculty, Bandırma Onyedi Eylul University, Bandırma 10200, Turkey; oder@bandirma.edu.tr
[5] Department of Naval Architecture and Marine Engineering, Maritime Faculty, Bandırma Onyedi Eylul University, Bandırma 10200, Turkey; aercetin@bandirma.edu.tr
* Correspondence: avinash.l@nmit.ac.in (A.L.); manjunath.mech@pestrust.edu.in (M.P.G.C.)

Abstract: The development of many engineered product applications for automobiles and aircraft parts has initiated the search for novel materials as alternatives to metal matrix composites (MMCs). Natural-fiber-reinforced polymer composites offer distinct advantages such as biodegradability, eco-friendliness, flexibility, low density, and higher specific strengths, etc. This study focuses on natural-fiber (hemp and banana)-fabric-reinforced polymer composites suitable for exterior-engineered parts. The hand lay-up process is used to fabricate these hybrid composites. Exterior-engineered products are highly susceptible to moisture, which can deteriorate their mechanical performances, including their tensile and flexural strength, thereby affecting the durability of the hybrid composites. Therefore, the hybrid composites are subjected to water absorption tests, where samples are immersed in distilled water for week-long intervals. After each interval, the water-absorbed specimens are tested for their tensile and flexural characteristics as per ASTM D-3039 and ASTM D-790, respectively. The moisture treatment had a notable impact on the composite materials, causing a slight decrease in the tensile strength by 2% due to the diminished lateral strength in the interlaminar fibers. Contrary to expectations, the flexural strength of the composites improved by 2.7% after the moisture treatment, highlighting the potential of the moisture treatment process to enhance the elastic properties of such composites. The dimensions of the specimens changed after the water immersion test, resulting in increased longitudinal and decreased lateral dimensions. The surface morphologies of the composite failure samples showed fiber delamination, fiber breakage, voids, and matrix fractures.

Keywords: moisture absorption; fiber-reinforced hybrid composites; hemp and banana fibers; SEM; mechanical characterization

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1. Introduction

Natural fibers tend to be more affordable than synthetic fibers due to their abundant availability and renewable nature [1,2]. The non-degradable nature of synthetic fibers leads to the generation of a large quantity of solid wastes [3]. Moreover, a few synthetic fibers possess an abrasive nature based on non-organic elements, which could damage machinery and potentially harm human health during the fabrication of composites [4,5]. Natural fiber composites (NFCs), with their inherent properties, such as a lower weight-to-strength ratio and density, superior mechanical strength (notably in specific strength

and modulus), outstanding acoustic adsorption properties, eco-friendliness, flexibility, and biodegradability, are increasingly being utilized in a variety of applications [6,7]. NFCs are being used to manufacture parts for aircraft and aerospace-engineered components [7], automobiles [8], ballistic and bulletproof jackets [6], and in the food packaging sector [9], among others. However, NFCs are promising materials beyond glass fiber for fabricating secondary structural components [10]. The following drawbacks must be avoided by natural fiber composites in order to ensure their self-sustainability and expand the aforementioned applications [11–13]: inconsistent chemical composition, fiber type and their hydrophilic nature, fiber dimensions, higher water absorption, and degradation. Therefore, determining the methods that improve the mechanical performances in NFCs is of industrial relevance.

The ageing process critically influences the microstructure properties of composite materials, such as the elastic modulus and hardness, thus impacting their longevity and efficacy in marine-based structures. Ghabezi et al. [14] studied the indentation characterization of glass/epoxy and carbon/epoxy composite samples aged in artificial salt water at elevated temperatures. This study showed significant reductions in these properties in both the carbon/epoxy (CE) and glass/epoxy (GE) samples after a 90-day exposure to artificial sea water at room temperature and at 60 °C. Degradation was particularly evident at the higher temperature, mainly impacting the elastic modulus. In a similar study, Liu et al. [15] investigated the hygrothermal aging behavior of carbon-fiber-reinforced polymer (CFRP) rods, which are extensively used in civil engineering due to their durability and mechanical robustness. Over a year-long immersion in distilled water, these rods exhibited a substantial decrease in the short beam shear strength (SBSS) and glass transition temperature due to the plasticization effect on the resin matrix and interfacial debonding. When comparing the ageing behavior of these commonly used composites to natural fiber composites, substantial differences are revealed. While natural fiber composites tend to exhibit an increased tensile strength and modulus with ageing, CE, GE, and CFRP display significant losses in mechanical properties over time. Further research is essential to understanding the underlying mechanisms of these differences, which are likely influenced by factors such as fiber–matrix interaction, fiber type, and the effects of water absorption. Such insights can facilitate a more informed selection of composites for specific applications, particularly those necessitating prolonged exposure to harsh environmental conditions.

In recent years, the surface treatment of natural fibers has enhanced the performance of fiber-reinforced composites [16]. The reinforcements can come in the form of laminate, particles, and short or long fibers extracted from the cellulose component of plants [17]. Natural fibers can be derived from various sources, such as plants, minerals, and animals [18]. The materials library is constantly expanding, and there are ongoing efforts to develop new natural fibers or identify existing ones that are best suited for engineering applications [19]. The most commonly used natural fibers include abaca, bamboo, banana, biduri, coir, collagen, cotton, hemp, kenaf, jute, pineapple, ramie, silk, wool, etc. [20]. Each of these materials possess its own specific properties, limitations, and applications. Their inferior properties, which are the limitations of most natural fibers, can be enhanced through surface treatment procedures [11]. Although the cost of surface-treating natural fibers is high, their energy requirement for composite fabrication (for example, hemp requires 4170 MJ/t) is significantly less than that of synthetic fibers (carbon requires 355,000 MJ/t, and glass requires 31,700 MJ/t) [21]. Natural fibers extracted from the stem of manau rattan result in better composite properties (thermal, chemical, mechanical, morphological, etc.) that are best suited for optoelectronics and aerospace applications [22,23].

Glass-fiber- and hemp-fiber-reinforced composites have been fabricated for applications in bus body parts [24]. Although the properties of hemp fiber are inferior to those of glass fiber, superior performance has been achieved in life-cycle assessments compared to glass fiber-reinforced composites [24]. A hybrid combination of sisal, flax, and hemp fibers have been used to fabricate door panels for Mercedes Benz [25]. Natural fibers, such as hemp and jute, offer excellent strength and acoustic absorption properties, making them

well-suited for use in automotive parts and other structural applications in agricultural, aerospace, automobile, construction, and sports products [10,20,26,27]. Hemp fibers with different aspect ratios result in various composite properties, including chemical, thermal, mechanical, and physical characteristics [28,29]. Hemp fiber, with its larger diameter, has shown better performance than other fibers such as wool, cotton, and acrylic in experimental studies [30]. Hemp exhibits better interfacial adhesion properties with thermoplastic polymers compared to other plant fibers like kenaf or jute when it acts as filler to create composites with better performance [31]. Reinforcing hemp fiber to a concrete matrix gradually reduces the composites water-absorption ratio and linear specific gravity [32,33]. Hemp fibers are potential materials that have found recent applications in textile industries [34,35]. Hemp fibers retain their shape for longer duration and rely on weather conditions, soil type, and cultivation [36,37]. Furthermore, using hemp fibers improves the composite properties, which could be enhanced if the fibers are further subjected to surface treatment (silane coating on fiber surface) [38]. Banana fiber can be extracted from the pseudo-stem of the banana plant, and its strain rates have been analyzed [39]. At lower strain rates, an increased strain results in its transformation from an amorphous to a crystalline nature, while catastrophic failure is observed at higher strain rates. However, catastrophic failure is observed at a higher strain rate. Banana fibers are abundantly available and pose a higher mechanical strength than jute, coir, bamboo, and hemp fiber [40]. In addition, the lower processing cost, reduced weight, biodegradability, and high strength ensure that ensure banana fibers are a potential alternative to synthetic fiber (i.e., carbon and glass) [40,41]. Banana fiber exhibited a higher specific strength (elongation and flexural) with a 50–60% banana fiber content in composites than a glass-fiber-reinforced composite [42]. However, an increased fiber loading raises the moisture absorption rate due to the increased porosity at the interface [33]. Composite laminates prepared with materials such as glass, banana, and hemp fibers reinforced with epoxy resin using the hand lay-up procedure were tested for mechanical strength and characterized by scanning electron microscopy (SEM) [43]. The SEM characterization revealed that the composite failure is attributed to fiber fracture, fiber pull-out and displacement, and internal structure failure on the fractured surfaces of the tested composites. Banana–hemp–glass-fiber-reinforced epoxy composites are potential alternatives to synthetic-fiber-reinforced composite material [43]. Synthetic fiber (polyphenylene sulfide with 40 wt.% of short glass fibers) composites are prepared for hood applications used in automotive sector [44,45]. The selected composites are subjected to the high temperature and ageing effects of cooling liquids [44,45]. The above literature review confirmed that mostly all of the reported works in this field have focused on producing composites suitable for interior automobile parts. However, the study of moisture absorption is of the utmost importance to extend their applications for a few parts that are ideal for the exterior surface of automotive parts.

To date, many research efforts have focused on fabricating natural-fiber-reinforced epoxy composites suitable for the interior parts of automotive parts. This study aims to study the impact of the moisture content of composite samples over time, particularly those intended for external automotive parts. The hybrid composite laminates were prepared with constituent fiber materials, with hemp and banana serving as the fiber reinforcements and polyester as the matrix, using the widely practiced hand lay-up technique. The hybrid composites reinforced with banana and hemp fibers were combined with those with single-fiber composites. Hemp fibers have a higher tensile strength and stiffness compared to banana fibers. Therefore, a hybrid composite reinforced with hemp fibers may have a higher overall strength and stiffness than a banana-fiber-reinforced composite. Banana fibers are lighter and have a lower density than hemp fibers. Therefore, a hybrid composite reinforced with banana fibers may be lighter in weight and have a lower density compared to hemp-fiber-reinforced composite. The cost and availability of banana and hemp fibers can vary depending on the region and market demand. In some locations, banana fibers may be more readily available and cost less than hemp fibers, while in the other locations, the opposite may be true. Banana and hemp fibers are considered environmentally friendly

alternatives to traditional reinforcing fibers. However, producing hemp fibers requires less water and fewer pesticides than banana fibers, making hemp fibers a more environmentally friendly choice [35].

This study contributes novelty to the field of material engineering by focusing on the behavior and durability of natural-fiber (hemp and banana)-fabric-reinforced polymer composites, which are emerging alternatives to metal matrix composites (MMCs) for exterior-engineered parts in automobile and aircraft applications. These composites, due to their biodegradability, eco-friendliness, flexibility, low density, and high specific strength, offer distinct advantages. Uniquely, this study explores how moisture treatment can impact the mechanical properties of these composites, which is a topic of critical importance given the vulnerability of exterior parts to moisture. Using the hand lay-up process to fabricate the composites, this research undertakes a rigorous water absorption testing regimen, examining changes in tensile and flexural characteristics over week-long immersion intervals. Contrary to expectations, this study unveils an intriguing phenomenon, where the moisture treatment improved the flexural strength of the composites by 2.7% while causing only a slight decrease in the tensile strength. This unanticipated result showcases the potential of moisture treatment to enhance the elastic properties of these natural fiber composites, offering new pathways for their application in industries requiring materials with improved flexural strength. Moreover, this study provides insights into the morphological changes in the composites post-moisture-treatment, including fiber delamination, fiber breakage, voids, and matrix fractures, contributing to a more profound understanding of these composites' behaviors under moisture exposure.

2. Materials and Methods

2.1. Materials

Hemp is one of the strongest and most versatile plants, capable of thriving in almost all climates. It is exceptionally robust, requiring minimal maintenance to grow healthily. A hemp plant is depicted in Figure 1a. The hemp fabric used for the current study, supplied by Spinning King Pvt. Ltd., in Ahmedabad, is displayed in Figure 1b.

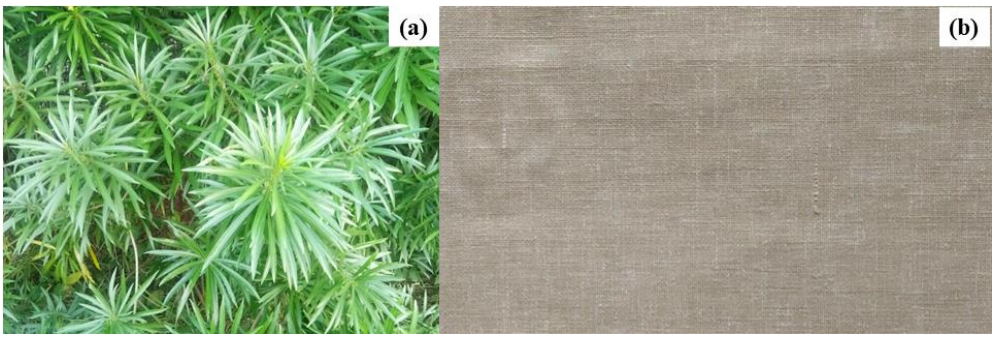


Figure 1. (**a**) Raw hemp plant and (**b**) textile hemp fabric.

India alone constitutes approximately 26% of global banana production, followed by China with 10%, Indonesia with 7%, Brazil with 6%, and so on. [46]. Banana plants thrive in warm, moist climates, including humid, subtropic, and semi-arid regions, provided they are not exposed to strong winds throughout the year [47]. A banana plant is depicted in Figure 2a. The woven banana fabric used in this study, supplied by M/s. Jolly Entrepreneur, Kolkata, is shown in Figure 2b.

The composite laminates were prepared using banana and hemp woven fabrics, specifically via the hand lay-up procedure. The properties of the woven fabric materials used in this study are presented in Table 1. It is notable that banana fiber has a higher density than hemp fiber, but hemp fiber exhibits a greater tensile strength and modulus of elasticity than banana fiber. The designations of the banana and hemp fibers are given in Table 2. Preliminary experiments were conducted to select the appropriate ratio of fiber to polyester resin and to examine the properties of the composite. The composition of 60% fiber and 40%

resin resulted in better properties and agreed with the published literature [48,49]. Natural fiber composites have been found in many industrial and automotive applications [50–53].

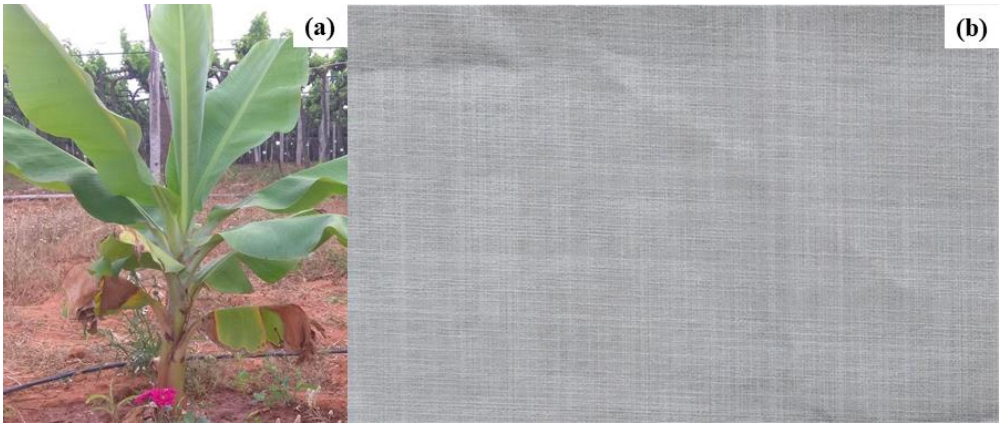


Figure 2. (**a**) Raw banana plant and (**b**) textile banana fabric.

Table 1. Physical properties of banana and hemp fibers [43].

Physical Properties	Banana Fiber	Hemp Fiber
Density, kg/m^3	1350	300–1300
Tensile strength, MPa	54	90
Modulus of elasticity, MPa	3.48	4.4
Moisture absorption, %	10–11	10–12

Table 2. Designation of banana and hemp fibers.

Sl. No	Sample	Composition
1	Sample A	60 wt.% hemp fiber + 40 wt.% of resin
2	Sample B	60 wt.% banana fiber + 40 wt.% of resin
3	Sample C	30 wt.% hemp fiber + 30 wt.% banana fiber + 40 wt.% of resin

Sample A comprised a composite material made of hemp fiber and resin. The hemp fiber served as the reinforcement material, while the polyester resin acted as the matrix. The combination of these elements resulted in the formation of hemp-fiber-reinforced composites. Sample B consisted of a composite material made of banana fiber and polyester resin. In this case, the banana fiber served as the reinforcement material, with the resin acting as the matrix. Their combination led to the creation of banana-fiber-reinforced composites. Hemp fiber, compared to banana fiber, possesses slightly different properties, such as greater strength and stiffness, as referenced in Table 1. Sample C was a composite material comprising banana fiber, hemp fiber, and polyester resin. The banana and hemp fibers provided reinforcement, while the polyester resin acted as the binder binding the fibers together. This mix resulted in the creation of hemp–banana-fiber-reinforced composites. The exact composition and properties of Sample C depended on the specific types and amounts of banana fiber, hemp fiber, and resin used. By combining banana fiber and hemp fiber, Sample C may have properties that fall somewhere between the properties of Samples A and B. For example, it may have a balance of stiffness and strength that is different from the other samples. The type and composition of the resin used also affected the overall properties of Sample C. The composition of a banana is as follows: 62–64% cellulose, 12.5% hemicelluloses, 5–10% lignin, and 4% pectin. On the other hand, hemp is composed of 81% cellulose, 14–22% hemicelluloses, 4–13% lignin, 0.9% pectin, and 0.8% waxes [4]. Overall, Sample C had unique characteristics based on the specific combination of banana fiber, hemp fiber, and resin used.

2.2. Polyester Resin Matrix

Polyester resin, supplied by Vikram Resins and Polymers in Bangalore, was used as a matrix material due to its excellent dimensional and thermal stability along with its outstanding mechanical and electrical properties [54]. Additionally, polyester resin possesses beneficial characteristics such as being lightweight, exhibiting strong adhesion, showing resistance to corrosion, and experiencing negligible shrinkage [55]. These properties make polyester resin a suitable material for various distinguished applications [56,57]. The properties of polyester resin are presented in Table 3.

Table 3. Properties of polyester resin [55].

Details of Properties	Value
Specific gravity	1.13–1.21 g/cm^3
Viscosity	250–750 μ(cP)
Tensile strength	22 MPa
Flexural strength	40 MPa

2.3. Hybrid Composite Preparation

The hand layup technique was employed to fabricate the composite laminate from the woven fabrics of banana and hemp fibers due to its ease of processing and economic benefits [58]. A significant advantage of the hand lay-up technique is its flexibility in design, as a technician can easily adjust the fiber orientation and resin content to meet the specific performance requirements of the composite. A solvent, often referred to as a 'thinner', was used to clean the work surface, ensuring the absence of dust or deposited particles. The use of a thinner is crucial in maintaining a clean and dust-free environment within manufacturing and laboratory settings. This practice helps to ensure the quality and accuracy of the products being produced or analyzed. Additionally, it enhances the safety of the work environment by reducing the risk of contamination and exposure to hazardous substances. A thin coat of wax (debonding agent) was applied on the cleaned surface to ensure a smooth surface finish [59]. Polyvinyl alcohol (PVA) is a biodegradable solution reagent that was laid on the mold surfaces, ensuring easy removal from the composite laminate [60]. Figure 3 presents the hand lay-up technique used to fabricate the composite laminate. The composite laminate was prepared with alternating layers of woven fiber matrix and polyester resin until the desired thickness was obtained.

Figure 3. Hand lay-up technique for fabrication of composite laminate.

2.4. Water Immerssion Procedure

Water immersion testing is used to understand how a composite material reacts to prolonged exposure to water. This is especially important for natural fiber composites, as they tend to absorb water, leading to various changes in their properties. The initial properties of the specimens, such as their weight and dimensions, were measured. The specimens were immersed in water at room temperature. The specimens were periodically

(at 1 week and 2 weeks) removed from the water and dried, and their properties were then measured. This included the weight gain due to water absorption as well as any changes in dimensions and mechanical properties.

2.5. Mechanical Properties of prepared Composite

2.5.1. Tensile Test

Three samples were prepared for each composite laminate (banana-fiber-reinforced composites, hemp-fiber-reinforced composites, and banana–hemp-fiber-reinforced composites) following the hand lay-up technique. The composite laminates were machined to the desired sample size as per the ASTM–D 3039 standard for conducting tensile tests [61]. The dimensions of the tensile test components were 150 mm in length, 25 mm in width, and 4 mm in thickness. The tests were conducted on the samples (Sample A, Sample B, and Sample C) at a strain rate of 0.00008 S^{-1} (i.e., displacement control at 0.2 mm/min). The test conditions agreed with the published literature [62]. For each composition (Sample A, Sample B, and Sample C), three replicate samples were prepared, and the average values of the three test readings were used to perform the analysis. The prepared specimens were dipped in water for two weeks. One set (three specimens for each composition) of samples (in wet condition) were taken after the first week, which was followed by drying and examined the tensile test viz. a computerized tensile testing unit. The specimens were fixed between the holder jaws, and rotating loading valves in the control unit applied continuous loading on the samples. After attaining a certain period, the testing specimen could not carry any further loading after reaching the ultimate load, and therefore fracturing of the specimens occurred at the breaking load. The fractured samples were examined using SEM to determine the failure's nature and causes. Figure 4 show the specimens dipped in distilled water. After the second week, the same procedure was followed to perform the tensile test for the remaining samples. The specimens required for the tensile testing were prepared as shown in Figure 5.

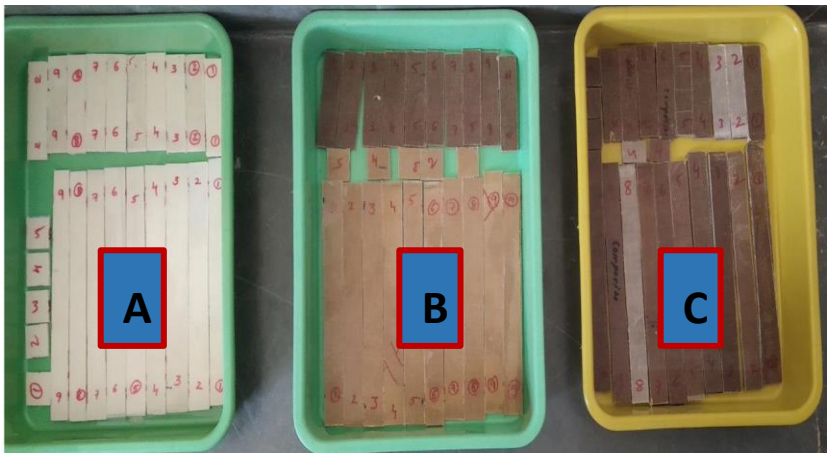


Figure 4. Testing specimens dipped into distilled water: (**A**) banana composite specimen, (**B**) hemp composite specimen, and (**C**) hybrid (hemp–banana) composite specimen.

2.5.2. Flexural (Three-point Bending) Test

Flexural strength tests were conducted to assess the flexibility of the specimens under different loading directions. The bending strength examination determined the ability of the composite laminated specimens to withstand a bending force applied perpendicular to their longitudinal axis. The test specimens were prepared in accordance with the ASTM D790 standard [61]. The dimensions of the flexural testing specimens were 90 mm in length, 25 mm in width, and 4 mm in thickness. After the flexural tests, the recorded readings were analyzed to determine the causes of failure, including an examination of the fractured surfaces via SEM. The flexural testing setup, along with the specimens, is represented in Figure 6.

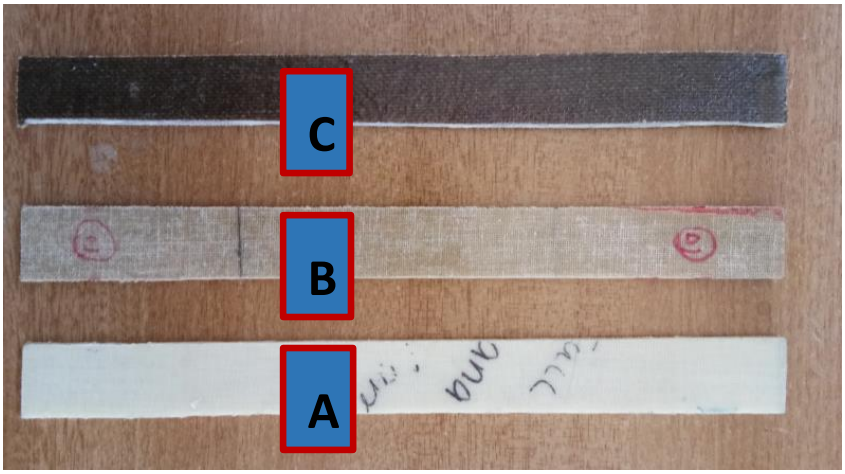


Figure 5. Moisture-treated tensile specimens for testing; (**A**) banana composite specimen, (**B**) hemp composite specimen, and (**C**) hybrid (hemp–banana) composite specimen.

Figure 6. Experimental flexural test specimen.

2.6. Water Absorption Test on Dimensional Stability and Weight

Natural fibers behave differently (both positive and negative impacts on fiber performance) under various environmental (dry and wet) conditions [63]. Water absorption affects fibers' wear rates (preventing the formation of debris layer) [64]. The samples were subjected to water absorption to determine the dimensional stability of the composites. For each composition (Sample A, Sample B, and Sample C), three replicate samples were prepared, and the average values of three test readings were used to perform the analysis. The weights of the samples (before and after water absorption) were measured using a digital weighing balance (accuracy of 0.001 mg). The specimens (without water immersion and dipped in water after the 1st week and 2nd week) were dried in an oven subjected to 60 °C for one day (24 h). The specimens were maintained in a desiccator to cool down at room temperature. The specimen weights were measured within a minute after removal from the environmental chamber. After measuring the weights, the samples' dimensions (length, breadth, and thickness) were measured. A similar procedure is employed in the published literature [36,65].

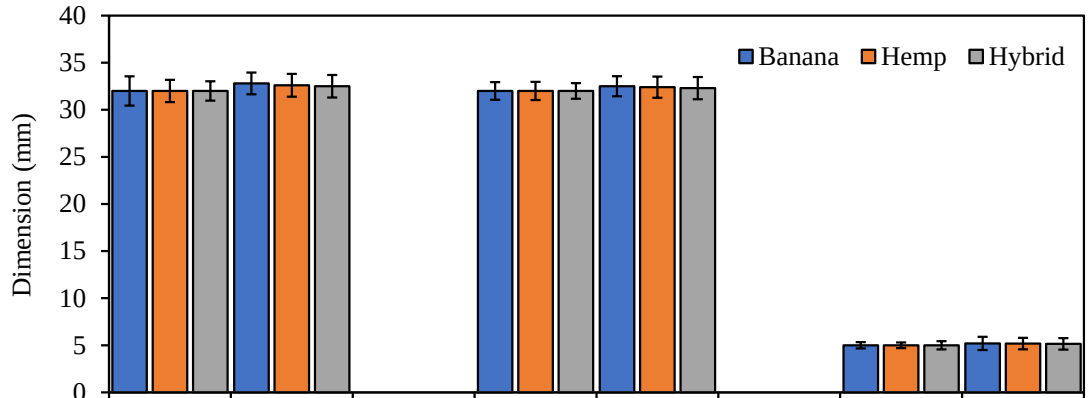
3. Results and Discussions

NFCs are increasingly being used across various industries, particularly for fabricating the interior parts of automotive applications. This research examined how properties such as changes in the weight, dimensional stability, tensile strength, and flexural capacity of composite laminates (banana-fiber-reinforced composite, hemp-fiber-reinforced composites, and banana–hemp-fiber-reinforced composites) varied with moisture absorption. The results are discussed in the following subsections.

3.1. Analysis of Results of Water Absorption on Dimension Stability and Weight

The specimens dipped in distilled water were taken out at two intervals for a 1-week duration. The effects of moisture absorption on the specimen dimensions (length, breadth, and thickness: 32 mm × 32 mm × 5 mm) were examined at varying times (refer to Figure 7). The standard deviations of three replicate experiments from the mean values corresponded to a change in dimensions (length, treated length, breadth, treated breadth, thickness, and treated thickness) after the 1st week (samples dipped in water) for the banana fiber (Sample B), hemp fiber (Sample A), and hemp + banana fiber (Sample C) were found to be equal to {±1.55, ±1.15, ±0.94, ±1.07, ±0.33, ±0.70}, {±1.18, ±1.21, ±0.96, ±1.12, ±0.30, ±0.61}, and {±1.03, ±1.2, ±0.83, ±1.18, ±0.44, ±0.61}. For the samples dipped in water and tested after the second week, the standard deviations of the dimensional changes in the samples for Sample B, Sample A, and Sample C were found to be equal to {±1.56, ±1.15, ±0.94, ±1.08, ±0.33, ±0.70}, {±1.19, ±0.65, ±1.34, ±1.12, ±0.30, ±0.61}, and {±1.02, ±1.18, ±0.89, ±1.13, ±0.44, ±0.41}. The banana and hemp specimens showed significant variations in length, breadth, and thickness. The strong lamination between the layers of the hemp and banana fibers, facilitated by the matrix, prevented the moisture from causing any disturbances. Although water absorption with the banana fibers, hemp fibers, and hybrid fiber composites was observed for the specimens examined after 1 week, their dimensional change after the first week to the second week was negligible (Figure 7).

After two weeks, the length, breadth, and thickness of the banana fibers changed by approximately 0.24%, 0.25%, and 0.96%, respectively. In contrast, the hemp fibers demonstrated a strong resistance to water absorption, with their length varying by around 0.15% and their breadth and thickness changing by approximately 0.22% and 0.77%, respectively. On the other hand, the hybrid specimens consisting of both hemp and banana fibers combined with polyester resin showed no significant changes, with variations of only 0.18% in length, 0.15% in breadth, and 0.58% in thickness.



	Original Length	Treated Length		Original Breadth	Treated Breadth		Original Thickness	Treated Thickness
Banana	32	32.8		32	32.5		5	5.2
Hemp	32	32.6		32	32.4		5	5.18
Hybrid	32	32.5		32	32.3		5	5.15

(a)

Figure 7. *Cont.*

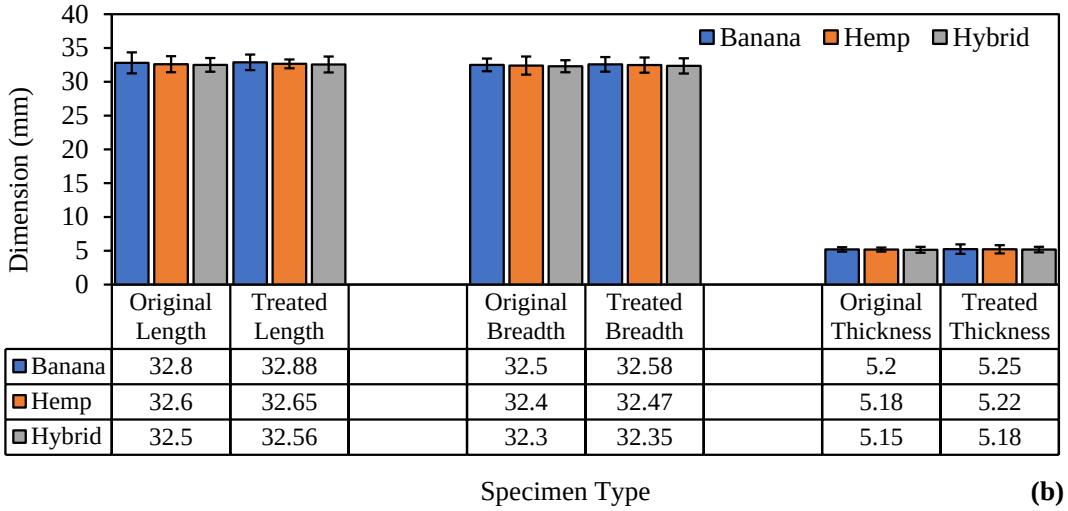


Figure 7. Changes in dimensions (length, breadth, and thickness) of moisture-treated tensile specimens: (**a**) first week and (**b**) second week.

The effects of moisture absorption on the weight of the specimens (5 gm of samples each from banana, hemp, and hybrid fiber composites) were examined over various periods up to 2 weeks (refer to Figure 8). The weights of the samples (three replicates each of Sample A, Sample B, and Sample C) corresponding to their original weights and their weights after being immersed in water for the 1st and 2nd weeks are presented in Figure 8**.** The standard deviations of the mean values from three replicate experiments corresponding to the original weights and weight changes after the 1st and 2nd weeks (for the samples immersed in water) for the banana fiber, hemp fiber, and hemp + banana fiber were found to be {±0.2, ±0.13, ±0.21}, {±0.22, ±0.22, ±0.18}, and {±0.28, ±0.28, ±0.2}. The weight of the banana-fiber-reinforced composite specimens showed negligible variation, whereas the weight of the hemp sample increased due to its superior moisture-absorption capability. However, the hybrid composite sample showed a significant effect on moisture absorption. It is interesting to note that although more moisture absorption was recorded, the sample's natural ability to evaporate the moisture quickly and retain its necessary properties. The maximum weight gain was recorded when the specimen reached a saturation point. The weight gain was a function of the square root of time for the tensile strength specimens after being submerged in distilled water at room temperature. It was observed that the water absorption was linear at the earlier stages and it fell slowly after reaching the saturation stage. In the samples with a 60% weight fraction of fiber, after 336 h of immersion in water, the maximum weight gain was 6.23%. This occurred due to the unevenness of the fundamental constituents of the fiber.

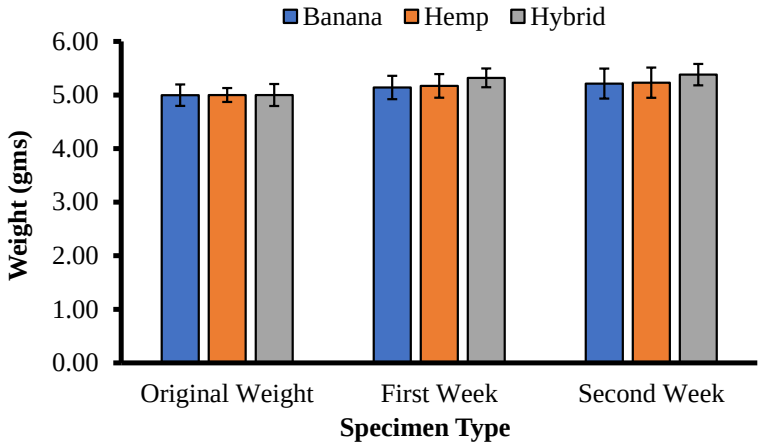


Figure 8. Changes in weight of moisture-treated composite specimens.

Similarly, for the samples with a 55% fiber volume fraction, the weight varied up to 8.71% [66]. The weight gain in the composites after soaking in distilled water was attributed to water diffusing into the material, leading to the formation of moisture-induced interfacial cracks and voids in the composites [67]. This led to the detachment of the fiber and matrix, resulting in structural failure. The covalent bonds between the fiber and matrix reduced the moisture absorption in the composite laminates [68].

3.2. Analysis of Results of Tensile Test

In this experimental study, tensile testing was conducted on three specimens each of the hemp-, banana-, and hemp–banana-fiber reinforced composite laminates. Figure 9 displays the failure zones of the tensile specimens. Figure 10 illustrates the variation in the tensile strength for each composite laminate after the specimens had been immersed in water for the first and second weeks.

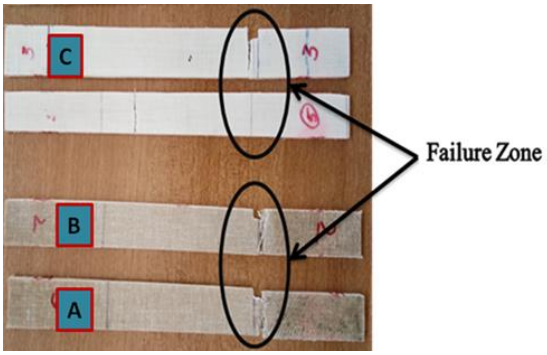


Figure 9. Tensile specimens after failure.

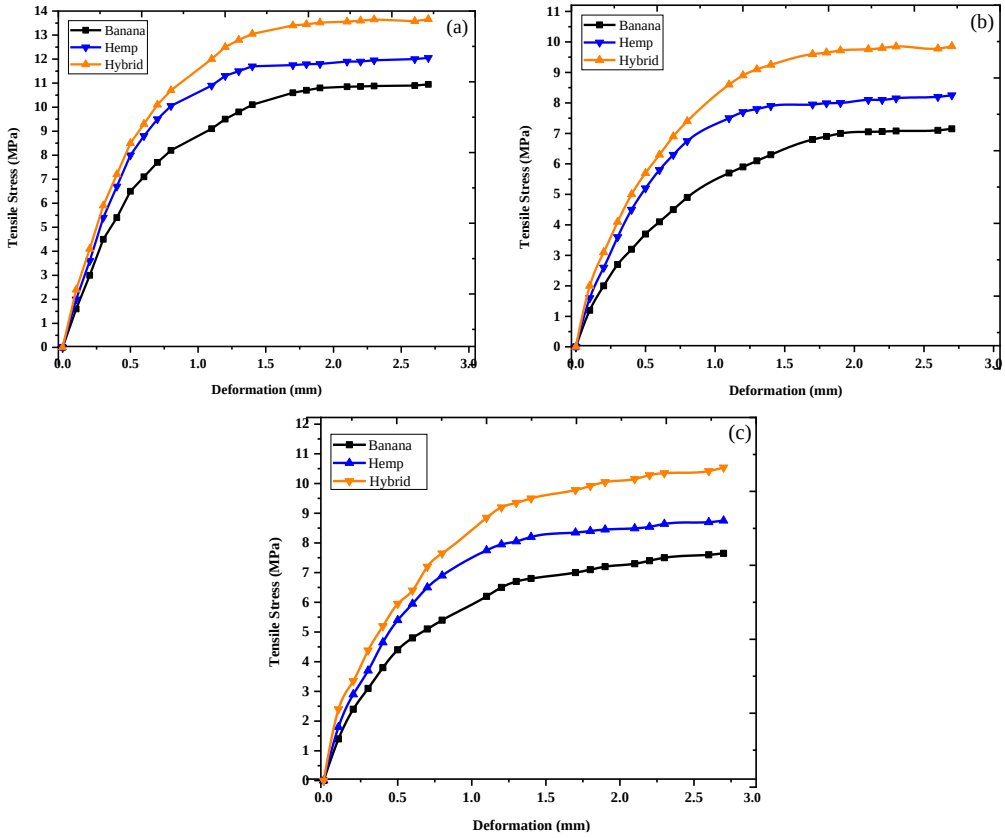


Figure 10. Composite laminate (banana, hemp, and banana + hemp) tested against different tensile loading conditions: (**a**) original specimen (without being dipped in distilled water), (**b**) specimen dipped in distilled water for first week, and (**c**) specimen dipped in distilled water for second week.

The presence of moisture content in hemp-, banana-, and hemp–banana-fiber reinforced composites can severely impact their tensile strength. Moisture can cause swelling or dimensional changes in the fibers, which can induce stresses and strains within the composite material. This can lead to reduced mechanical strength, stiffness, and other adverse effects such as delamination or fiber–matrix debonding. Moreover, moisture can promote the growth of microorganisms such as fungi or bacteria, further weakening the composite material. Therefore, it is essential to consider the moisture content carefully and take measures to minimize its impact on the composites' mechanical properties [69]. The composite laminates (banana-fiber-reinforced composite, hemp-fiber-reinforced composites, and banana–hemp-fiber-reinforced composites) were tested against different tensile loading conditions for the unaged specimens (without dipping into distilled water). The specimens dipped in distilled water for the first and second weeks are shown in Figure 10. The tensile stress values of Sample A, Sample B, and Sample C for the unaged specimens and the specimens dipped in distilled water for the first week and the second week were {12.05, 10.95, and 13.66 MPa}, {8.35, 7.45, and 10.16 MPa}, and {8.55, 7.65, and 10.24 MPa}, respectively. The hybrid composites resulted in higher tensile strengths than the banana- and hemp-fiber-reinforced composites under different environmental conditions. The performance of the specimens treated with distilled water for the first and second week resulted in negligible variations (Figure 10b,c). The strength values were comparatively lower for the samples dipped in water than for the unaged samples. The composites in the distilled water underwent fiber swelling due to their hydrophilic characteristics. Therefore, the samples dipped in water were more susceptible to debonding between the matrix–fiber interfacial adhesion characteristics (development of swelling stress between matrix–fiber interface causes debonding) in the composites. The results agreed with the published literature [36,70].

The hemp specimens absorbed more moisture compared to both the banana and hybrid composites. After being immersed in distilled water for two weeks, the tensile strength of the hemp specimens decreased by 4.375%, which was attributed to hemp's greater water absorption. Similarly, the tensile stress for the banana composites was reduced by 3.748%. However, the hybrid composite specimens exhibited a tensile stress variation of only 1.98%. These lesser variations in tensile strength were attributed to the superior properties that facilitated quicker moisture evaporation. As time progressed, the amount of water absorbed by the natural fibers increased and decreased the bonding strength between the adjacent layers, resulting in fiber delamination. The aforementioned reasons are critical for fracture mechanisms. The tensile stress variation in the different specimens with time is represented in Figure 10a–c. The low tensile strength in the composites was attributed to the voids or discontinuities formed during the curing or setting process [68–71]. Note that the voids were stress raisers responsible for initiating and propagating cracks during the tensile strength examination. The tensile strength of treated composites decreased with the increase in the fiber loading. This occurred due to the formation of large blocks or holes, and an uneven or irregular fiber arrangement initiated stresses followed by cracks between the interfaces.

3.3. Analysis of Results of Flexural Test

The composite laminate specimens were prepared according to the ASTM D790 dimensions and tested using a computerized universal testing machine. The flexural strength increased with the moisture content due to the enhanced elastic properties. However, the degree of this increase depended on the specific composition and processing of the composite. It is important to note that while some increase in the flexural strength may be observed with increased moisture content, an excessively high moisture content can reduce the mechanical strength due to various factors, as discussed previously. Figure 11 provides a visual representation of the failure of a flexural test specimen, which can occur due to various factors such as excessive loading or defects in the composite material. It is essential to carefully evaluate the causes of any failures and take appropriate measures to

address them, such as improving the processing or composition of the composite material or adjusting the testing parameters.

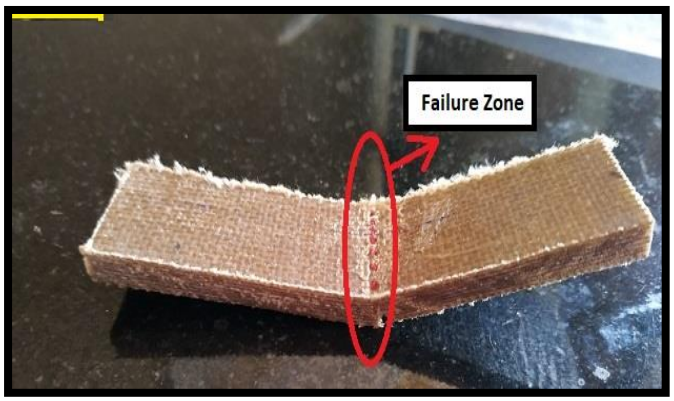


Figure 11. Three-point bending of moisture-treated test specimens after failure.

Studying the sagging and hogging of the prepared specimens offered another approach to analyzing the bending behavior. This type of investigation helps to suggest the most suitable material for heavy-load marine parts and the exterior parts of automotive applications. The results from the three-point bending stress experiment are plotted and shown in Figure 12. It is clear that the moisture played a prominent role in deciding the flexural strength. The flexural strength of all the samples was tested under different environments (unaged or without the samples being dipped in distilled water and samples with distilled water after immersing them in water for the first week and second week). The flexural strength values of Sample A, Sample B, and Sample C for the unaged specimens and the specimens dipped in distilled water for the first week and the second week were {50.19, 45.58, and 53.33 MPa}, {51.19, 46.58, and 54.33 MPa}, and {51.48, 47.07, and 55.01 MPa}. The hybrid composites resulted in a higher flexural strength than banana- and hemp-fiber-reinforced composites under different environmental conditions. Interestingly, the flexural strength increased after exposure to a moist environment. An increase in the ductility of the composites occurred due to the plasticization impact of the water absorption, resulting in an increased fracture toughness [72]. Similar observations are reported in the published literature for composite samples subjected to water for 30 days [73]. In this work, the bending strength of the banana, hemp, and hybrid (banana + hemp) samples increased to 1.4%, 1.8%, and 2.7%, respectively. When the hemp and banana specimens were compared, the hemp specimen exhibited very good elastic properties and moisture-absorption capabilities. Although the composite samples had good moisture-absorption characteristics, their effect on the bending strength was negligible. This is the important theory, based on which we can successfully suggest one of the best alternatives to marine and automotive applications. The flexural stress–strain values of the samples immersed in distilled water decreased with an increased immersion time. Higher moisture absorption led to a higher degradation rate. Moisture absorption led to the weakening of the fiber and matrix linking. While immersing the composites in water, the open holes (voids) and cracks that formed within the composites were permeated with water, and the absorbed water particles acted as an emollient (softener), which refined the bending strength and stiffness [74]. The flexural strength of the PALF/polyester composite increased with an increase to 20 wt.% of fiber loading, which depreciated slowly from 30 wt.% to 40 wt.% of fiber loading. At 20 wt.% of fiber loading, the flexural strength of the composites increased by about 24% compared to the polyester matrix. Related to the composites, the protection against inter-laminar fracturing controls the flexural capabilities. A better inter-laminar bonding of the fiber–matrix interface represents a higher flexural strength [75]. The fracture strength of coconut-coir–sisal hybrid epoxy composites at 20 wt.%, 30 wt.%, and 40 wt.% were 47 MPa, 58 MPa, and 66 MPa in wet conditions. The percentage reduction would be between 9% to 14% compared to dry samples. The flexural strength of the wet specimens

increased with the fiber content, and the resulting moisture absorption made the fibers swell. The above reasons resulted in the propagation of shear stress at the interface, which caused de-lamination and de-bonding between matrix and fibers [76].

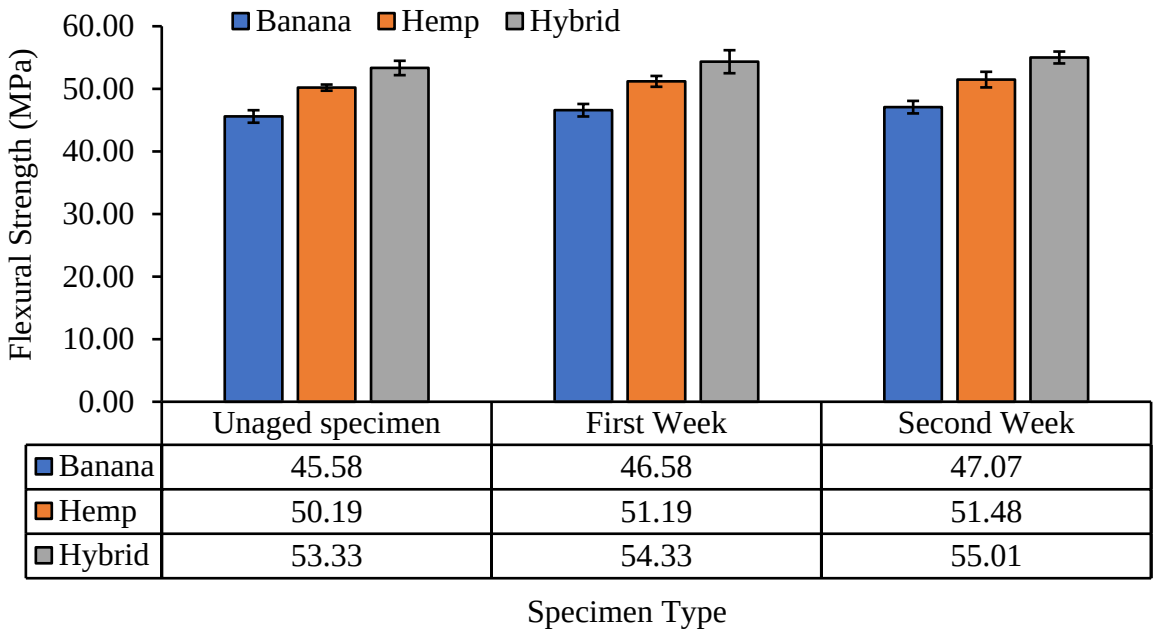


Figure 12. Flexural strength examination of composite laminate with varying time.

3.4. Fracture Surface Analysis of Composite Samples

Figure 13 depicts the fractography of the different composites, where Figure 13a,b represent the fiber diameter at lower and higher magnifications. Figure 13a,b represent the hemp fiber sample with a fiber content of 60%, which displayed good strength and bonding (see Figure 13a). In addition, it can be observed that there was a strong bonding between the matrix and fiber, as depicted in Figure 13b. Strong bonding helps to shift stress uniformly between a fiber and a matrix [66]. Overall, it can be observed that the critical factor affecting the mechanical behavior of the synthetic fibers was the affinity among the fibers. Figure 13b shows a strong bond between the hemp fiber and the polyester resin. Strong bonding was achieved by the adherence or wetting abilities at the hemp-fiber–polyester interface surface [77]. Figure 13c,d represent the fiber diameter at lower and higher magnifications. Figure 13c,d represent the banana fiber sample with a fiber content of 60%, which displayed good strength and bonding (see Figure 13c). From the figures, we can see cracks at a few places, which may be due to the continuous loading on the specimen. In addition, the fibers started to crack and propagate until the failure occurred. Strong bonding was achieved by the adherence or wetting abilities at the banana-fiber–polyester interface surface [77]. Figure 13e represents a hybrid composite, i.e., 30% hemp fiber and 30% banana fiber. From Figure 13e, the enumeration 1 represents hemp fiber, and 2 illustrates banana fiber.

Figure 13e shows strong bonding due to the adherence or wetting abilities at the hemp-fiber–polyester interface surface. From the fractography (Figure 13a–e), we can conclude that the fibers were strongly bonded with the matrix, and a minimal number of fibers that were pulled out from the surface can be observed. The moisture-absorbed composites indicated a high tensile strength and modulus. The mechanical properties of the moisture-treated composites relied on the temperature, fiber amount, and duration of immersion. Moisture decreases the mechanical performance of lignocellulosic polymers [78], which are present more in hemp and banana fibers and the composites were prepared from these two types of plant fibers. When the linear tensile load applied on the specimens resulted in fiber pull-out, it caused a reduced binding energy and pushed the fiber particles out during loading [79–81].

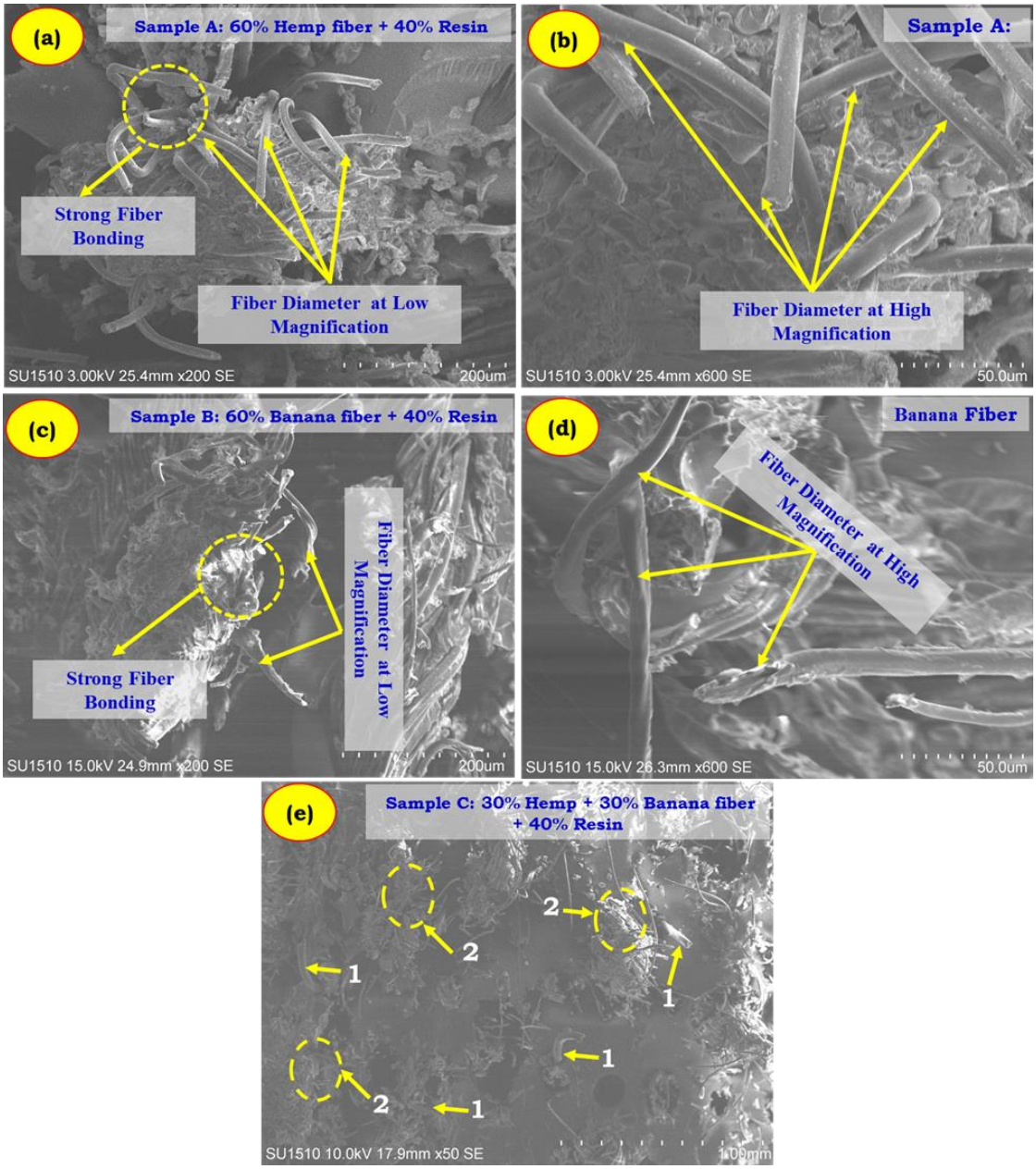


Figure 13. Fracture surface of hemp fiber composite, banana fiber composite, and hemp–banana fiber composite, where (**a**,**b**) denote the fiber diameter of hemp fiber at lower and higher magnifications, (**c**,**d**) represent the fiber diameter of banana fiber at lower and higher magnifications, and (**e**) denotes hybrid polymer composite (combination of hemp (denoted by 1) and banana fiber (denoted by 2)).

4. Conclusions

Experimental investigations were conducted to examine water-absorbed natural-fiber (banana and hemp)-reinforced hybrid polymer composites that are suitable to use in exterior engineered parts. The obtained results are discussed as follows:

1. The effect of the moisture absorption on the hybrid composites immersed in distilled water was studied at room temperature. There was no significant change in the dimensions of the specimens. The weight of the hybrid composites increased due to the water particles absorbed by the fibers due to their higher cellulose content. A higher level of water absorption decreased the fiber strength as a result of the formation of micro-voids on the surfaces;

2. The moisture absorption resulted in fiber swelling, resulting in reduced mechanical strengths. The increased degradation rate of the fibers due to the water absorption (after the prolonged immersion of the composites for two weeks) resulted in a reduced tensile strength;
3. The hybrid (hemp and banana)-fiber-reinforced polymer composites resulted in a higher tensile strength than the other composite specimens. The tensile strength of the hybrid composite was 11% greater than that of the hemp and banana raw specimens. The tensile strength decreased to 2% in the second week due to moisture absorption;
4. The flexural strength of the hemp–banana hybrid composite increased to 2.7% within one week (i.e., from 1126 MPa–1152 MPa);
5. The SEM morphology study revealed fiber breakage and matrix fracturing due to the decreased matrix strength as a result of the absorbed moisture in the composite samples. Voids and fiber dislocations were also observed in the fractured samples;
6. Overall, it can be concluded that the hemp fiber alone produced better properties than the banana fiber. The hybrid (hemp and banana) composites resulted in enhanced properties that are best suitable for exterior-engineered parts.

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