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Investigation of Mechanical Properties of Bamboo Fiber Reinforced Polymer Matrix Composite for Structural Applications

Jigar Suthar, Divyang Pandya
LDRP Institute of Technology and Research, Kadi Sarva Vishwavidyalaya, Gandhinagar, Gujarat-382006

Kaushik Patel
Institute of Technology, Nirma University, Ahmedabad, Gujarat-382481

Abstract - In India, bamboo is an ancient building material used for a diversity of purposes. In the global south, bamboo is commonly used for frames, bridges, housing, and temporary structures. In order to satisfy the widespread demand for affordable housing, bamboo has proven to be both inexpensive and abundant in global south countries. This study concentrates on the mechanical properties of bamboo fiber-reinforced polymer composites for use in structural industries. In addition, a bamboo fiber-reinforced composite outperformed glass fiber in a few areas when compared in a variety of ways with glass fiber. Investigations uncovered the potential use of bamboo fiber-reinforced composites with high rigidity but lower strength limitations than glass fiber composites. E-glass epoxy composites have attained a tensile strength of 40.53 MPa and a hardness of 68.2 RHN. However, the results of composites reinforced with bamboo fibers cannot be ignored. To enhance the mechanical properties, additional research was conducted, and the results were satisfactory.

***Key Word*: Green Composites, Bamboo fibers, Glass fibers.**

1. INTRODUCTION

Indian history mentions the use of composite bows by different individuals during the Mahabharata war. Pinak, Gandiva, Vijaya, and Shranga are some examples of these bows. In particular, the Agni Purana and Kautilya Arth Shastra contain information on these weapons. [1]. Stones or bellies were used to reinforce the center of these bows, while sinew was used for the back [2]. In addition, nature provides composite materials such as wood, which consists of cellulose fibers and lignin [3]. Consequently, the concept of composites is not novel to the human race. However, composite materials have been the most promising materials for the past 35 years [4]. The number of applications and the volume of composite materials have significantly increased, resulting in the persistent creation of new markets [5, 6]. Modern composites constitute a substantial proportion of engineered materials [7]. These contemporary composites are in high demand because they are lighter than their predecessors. Nonetheless, cost reduction remains a challenge for scientists and businesses [5]. Because of this, many researchers and businesses are working on making it possible to mass-produce composite parts at a reasonable cost. This has led to the development of new and innovative manufacturing methods [8]. However, employing new and innovative manufacturing techniques will not have a significant impact unless all aspects, including design, tooling, quality assurance, and programme management, are taken into account in order to compete with metals [9, 10].
The composite industry shifts its focus away from the aerospace industry in pursuit of large business opportunities due to the size and scope of the transportation industry[11, 12]. High performance Fiber Reinforced Polymer (FRP) matrix composites could be used in a wide variety of applications, including explosive resistant armour, fuel cylinders for natural gas cars, support beams, industrial drive shafts, windmill blades and paper-making rollers [13]. Moreover, the construction industry is seeking lighter, seismically resistant materials that not only reduce a structure's overall dead weight but also absorb vibrations [14]. As a direct result, composites are utilized in a vast array of structural applications for the seismic retrofitting or strengthening of existing structures [15]. Composite materials have two or more layers that are different from each other physically and/or chemically. In addition, an interface phase exists to separate two or more phases, and its characteristics cannot be described by any of the phases in isolation [16]. The majority of composite materials consist of a continuous matrix phase and a non-continuous reinforcement phase that is stiffer and stronger than the matrix phase.[17, 18]. In contrast, traditional fibers and/or composites such as glass, carbon, or aramid fibre-reinforced thermoplastics and thermosetting polymers are not eco-friendly [19]. Consequently, one of the remedies proposed by researchers is composites reinforced with natural fibers [20]. It encompasses plant, animal, and mineral-based natural fibers. Furthermore, natural fibers can be categorized according to their origin [21]. Figure 1 illustrates the specific classification.

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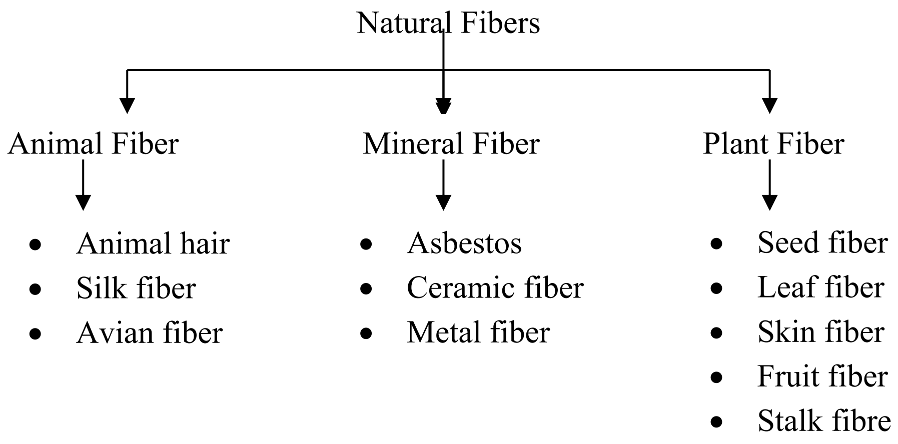

Fig 1. Classification of the natural fibers [22].

FRP composites' properties are significantly affected by the manufacturing process. This is due to the fact that variations in fiber orientation have a profound effect on the composite's mechanical properties [23]. This change in orientation can be controlled by the manufacturing process that combines the polymeric resin with the desired fiber reinforcements [24, 25]. There are two types of methods for making FRP composites: open mold and closed mold [26]. The processes for both open and closed molds are depicted in Table 1.

Table 1. Types of composite manufacturing processes [27, 28] .

Open Mold Processes	**Closed Mold Processes**
Hand lay-up process	Compression molding
Spray up process	Injection molding
Vacuum-bag auto clave process	Sheet molding compound (SMC) process
Filament winding process	Continuous pultrusion process

Jhu, Yang [29] examined the mechanical, thermal, and water absorption properties of bamboo fiber-reinforced starch/polypropylene composites. Researchers have created composites using injection molding and extrusion techniques. In addition, soil burial and microbe medium degradation were conducted to determine the effect of different mediums on composites. It was discovered that bamboo fiber and starch have a significant impact on the material's properties. The addition of bamboo fiber enhances the flexural strength and biodegradability of composites. Wang, Lu [30] examined unprocessed bamboo fibers in NaOH solution and unprocessed bamboo fibers. Using a technique of hot pressing developed by the researchers, bamboo fiber-reinforced composites were produced. Using tensile and micro-bond experiments, modulus, elongation at break, tensile strength, and interfacial strength were determined. In addition, scanning electron microscopy (SEM) was utilized to assess the component defects. In addition, a thermogravimetric analysis was conducted to determine the impact of alkali concentration on the composite. According to the researchers, the strength of composites containing NaOH-treated bamboo fibers increased by 45.24 percent compared to untreated fibers. The elongation at break increases as the concentration of fibers increases. However, contrary to conventional belief, as concentration increases, modulus decreases. Pani, Nayak [31] conducted comparable research. To evaluate the mechanical properties of natural and synthetic fiber-reinforced polymer composites under a variety of environmental conditions, scientists fabricated a number of composites reinforced with natural and synthetic fibers. They came to the conclusion that natural fiber-reinforced composites break down faster than their counterparts in seawater and humid environments. In addition, they proposed combining composites reinforced with glass, bamboo, and jute fibers so that composites retain satisfactory mechanical properties. Mousavi, Zamani [32] looked into different kinds of natural fibers, such as those from plants, animals, and minerals. In addition, researchers conducted a comprehensive analysis of case studies concentrating on the mechanical properties of bamboo fiber-

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reinforced polymer composites. They concluded that bamboo fibers are one of the most effective natural fibers for polymer matrix composites. However, altering the structure of the fiber with an alkali solution treatment further enhances the composites' mechanical properties. It was also advised that production methods be improved. Santhosh, Praveena [33] utilized a hand-layup technique to produce bamboo fiber-reinforced composites and studied the impact of fiber amount and distribution on mechanical properties. The researchers came to the conclusion that a high fiber content increases the flexure, tensile, and impact strengths of composites. Additionally, it enhances damping characteristics. The strength of the composite is increased by the uniform distribution of fibers. Unlike other academics, contrary to the findings of other researchers, Santoth et al., (2022) observed matrix phase deformation and attributed it to the degradation of mechanical properties. In order to further enhance the material's properties, various fabrication techniques and the optimal use of epoxy resin were suggested.

2. RESEARCH METHODOLOGY

The bamboo fibers put to use in this investigation were extracted from plants cultivated in the Dang district of Gujarat. The long filaments were extracted using a combination of both chemical and mechanical methods after preliminary studies yielded encouraging results. Prior to being crushed with a crusher machine, bamboo was chopped longer than the necessary length for the specimen (165 mm) and dried in sunlight for two weeks. The bamboo was then immersed for an hour at ambient temperature in a 5% NaOH solution. The solution was then removed from the fiber surface by washing the fibers four times with distilled water. The fibers were then dried in an oven at 800 degrees Celsius for five hours to remove moisture before being stored in polyethylene containers to prevent contamination. The diameter of the extracted bamboo was then measured. It was discovered that the diameter was between 300μm and 700μm. Fig. 2 depicts the bamboo-fiber-reinforced composite.

Fig 2. Bamboo fiber reinforced polymer composite.

Following the placement of eight handcrafted fiber sheets (0.29–0.32 mm in thickness) in the mold, an epoxy resin and curing agent mixture was added. The composite plate was produced using a 180×180×3 mm3-capacity mold. A 8329 epoxy mold release agent was applied to the mold before the fibers were inserted to prevent the composite from attaching to the metal. While pouring the mixture into the mold, a propane torch was used to eliminate the bubbles that formed. The composite plate was then allowed to cure for eight hours at ambient temperature. The mold was then inserted in a press molding machine for three hours of 60 °C hot pressing. Similar steps were taken to create a glass fiber-reinforced composite material, with the exception that glass fiber twill sheets (260 gsm) were purchased from Vruksha Composites in Andhara, India, and used directly without pretreatment.
Using diamond-coated blades, the specimens were cut to the requisite dimensions of 165×19×3 mm3. ASTM D792 was utilized to ascertain the composite's density. The tensile strength was determined using a universal testing machine compliant with ASTM D638-10. All specimens were run at 5 mm/min cross-head speed at room temperature and 50% relative humidity. The average values of three samples of each composite were recorded for analysis. In accordance with ASTM E18, a Rockwell hardness test was also conducted to ascertain material strength and wear resistance [34]. The orientation and distribution of the filaments were

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determined using an inverted Olympus GX51 metallurgical microscope for microscopic analysis. Additionally, SEM-EDX analysis was performed to investigate the structure and composition of composite plates.

In addition, additional research and a review of the relevant literature were conducted after initial experiments revealed problems. The literature review revealed solutions to issues such as the uneven distribution of fibers and the construction of separate layers of epoxy as a result of the use of propane gas. However, the results of the alkali treatment of bamboo fiber were inconsistent. The findings of Rajeshkumar and Hariharan [35] and Yan and Chouw [36] indicate that treated fibers enhance the mechanical properties of composites. As a result, additional experiments utilizing a combination of hand layup and vacuum bag technique (VBT) were conducted in order to eliminate the issues caused by the hand layup procedure. In addition, untreated and treated bamboo fibers were used in the experiments to determine the effects of alkali treatment on the composites' mechanical properties.

The fibers for the additional investigation were soaked for one hour at room temperature in a solution containing 5%, 10%, and 15% NaOH. The surface of the filaments was then washed four times with distilled water to remove the solution. The fibers were then dried in an oven at 80 °C for five hours to eradicate any remaining moisture before being stored in polyethylene bags to prevent contamination. In addition, untreated fibers were used in the additional study. The samples for the additional experiments were created by emptying the epoxy-hardener mixture to the marked line and then inserting eight sheets of handcrafted twill bamboo fiber. The remaining space in the mold was then filled with a mixture of epoxy and hardener. The ratio of epoxy resin to hardener in the composition was maintained at 1:1. The act was then removed from the mold and inserted inside a flexible bag. The negative pressure generated by a hoover accomplishes the uniform distribution of the mixture around the fiber sheet and maintains the fiber's initial position. The composite plate was then allowed to cure at room temperature for eight hours prior to being placed in an electric oven at 600 degrees Celsius for approximately three hours. The samples were then cut according to the standards ASTM D638-10 and ASTM E18.

3. FINDING AND DISCUSSION

Table 2 displays the average ultimate tensile strength of composites reinforced with glass and bamboo fibers. The outcomes indicate that the tensile strength of the two materials is comparable. In structural applications where the applied tensile force is less than 39 MPa, this indicates that both materials can be used. Alternatively, bamboo-fiber-reinforced composite samples have marginally greater strength than glass-fiber-reinforced composites. Table 3 displays the average Rockwell hardness of both composite materials. Rockwell hardness is significantly different between the two materials. Compared to bamboo fibers, glass fiber is twice as tough. Hence, glass fiber composites are suggested for uses where a high level of hardness is required. Moreover, as shown in Table 4, % elongation at break produces comparable results. In comparison to bamboo fiber composites, the elongation of glass fiber composites is preferable.

Table 2. Average tensile strength of glass and bamboo fibers reinforced composites.

Sr no.	Material	Average Ultimate Tensile strength (MPa)
1	E-glass reinforced epoxy resin composites	40.53 ± 3.1
2	Bamboo fiber reinforced epoxy resin composites	40.93 ± 3.5

Table 3. Average Rockwell hardness of glass and bamboo fiber reinforced composites.

Sr no.	Material	Average Rockwell Hardness (RHN)
1	E-glass reinforced epoxy resin composites	68.2 ± 5.3
2	Bamboo fibre reinforced epoxy resin composites	32.3 ± 3.2

Table 4. Average % elongation at break of glass and bamboo fiber reinforced composites.

Sr no.	Material	% Elongation at break
1	E-glass reinforced epoxy resin composites	3.8 ± 0.3
2	Bamboo fiber reinforced epoxy resin composites	2.6 ± 0.5

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The irregular distribution of the fibers is one of the causes of the decrease in bamboo fiber′s hardness and percent elongation. The irregular distribution is primarily due to the handcrafted bamboo fiber sheet as opposed to the machine-woven twill pattern of the glass fiber fabric. As shown in Figure 3, the handcrafted sheets have more space between the fiber filaments. Figure 3(a) depicts microscopic images of bamboo fiber composites with a spacing greater than 25 µm. However, compared to bamboo fiber sheets with a manual twill pattern, glass fiber sheets have a substantially smaller gap between strands [37, 38].

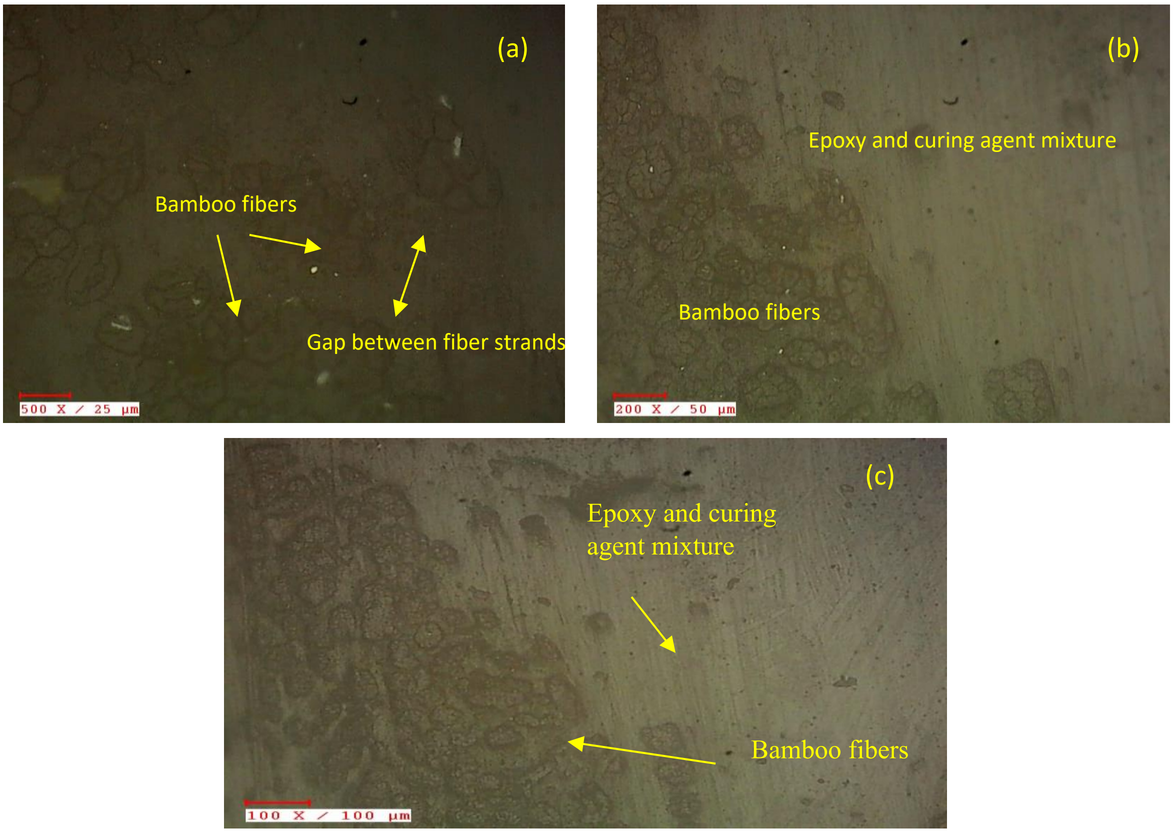

Fig 3. Microscopic images of composite plates at different magnifications; (a) 100 µm, (b) 50 µm and (c) 25 µm.

In addition, Fig. 4(a) depicts an SEM image of the bamboo fiber composite, which reveals the asymmetrical distribution of individual fiber strands. Figure 4(b) depicts a layer of epoxy and curing agent mixture that has separated. This may be due to the use of a propane torch on the composite's upper surface, which accelerates the curing process compared to the mixture beneath the top surface. Figures 4(c) and (d) depict the irregular curing of various composite layers. Figure 4(d) depicts a toughened and softer portion of the composite's outer layer. This suggests that not even the upper layer is cured uniformly. Examine Figure 4(c), which depicts the same phenomenon in the vicinity of the fibers, beneath the surface. The authors believe that the aforementioned factors are responsible for the deterioration of the mechanical properties of bamboo fiber-reinforced polymer composites. Therefore, the authors advocated for a fabrication process that uniformly cures composites.

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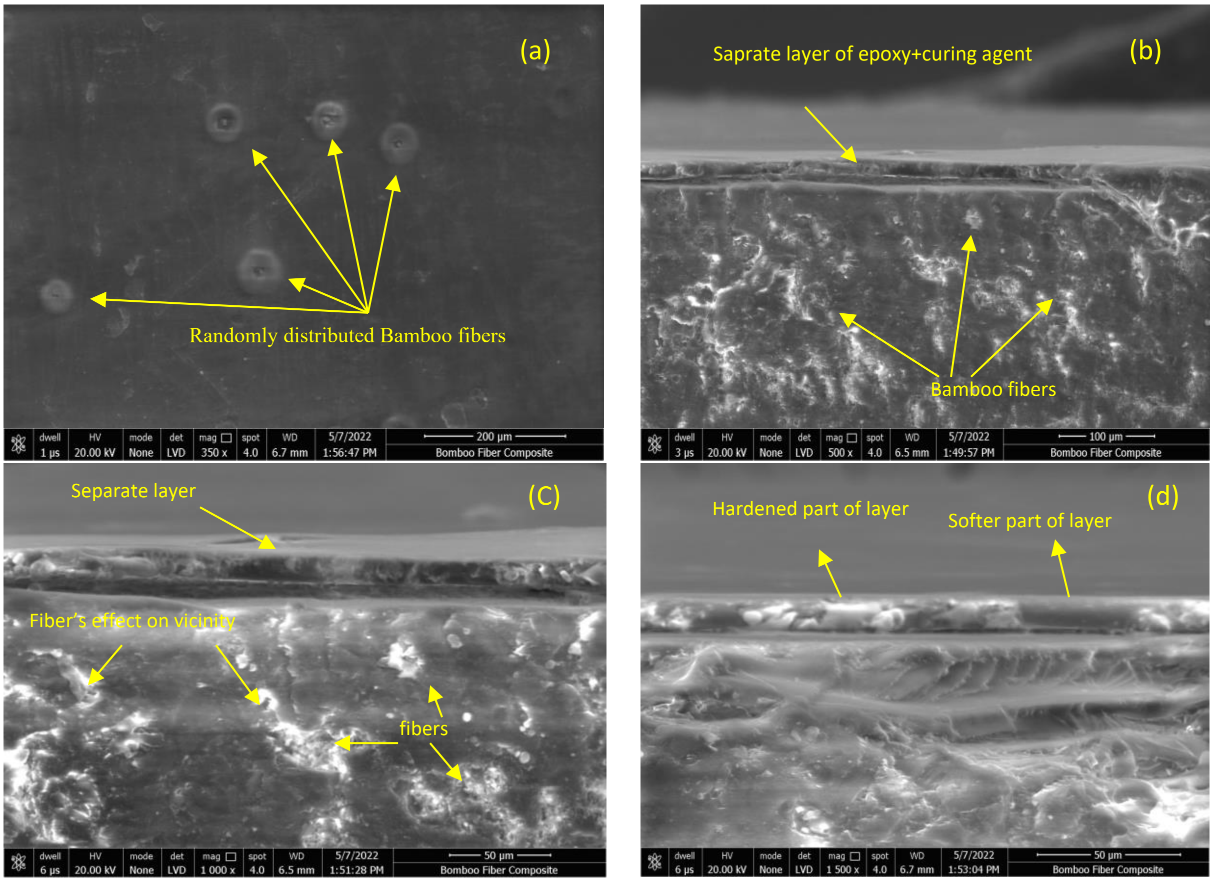

Fig 4. Scanning Electron Microscopic images of bamboo fiber reinforced composites at different resolutions.

Additionally, an SEM-EDX analysis was conducted to validate the composite composition and Fig. 5 results. The graph reveals that the composite consists of 61.34 percent carbon, which reflects the quantity of bamboo fiber and/or epoxy-curing agent mixture.

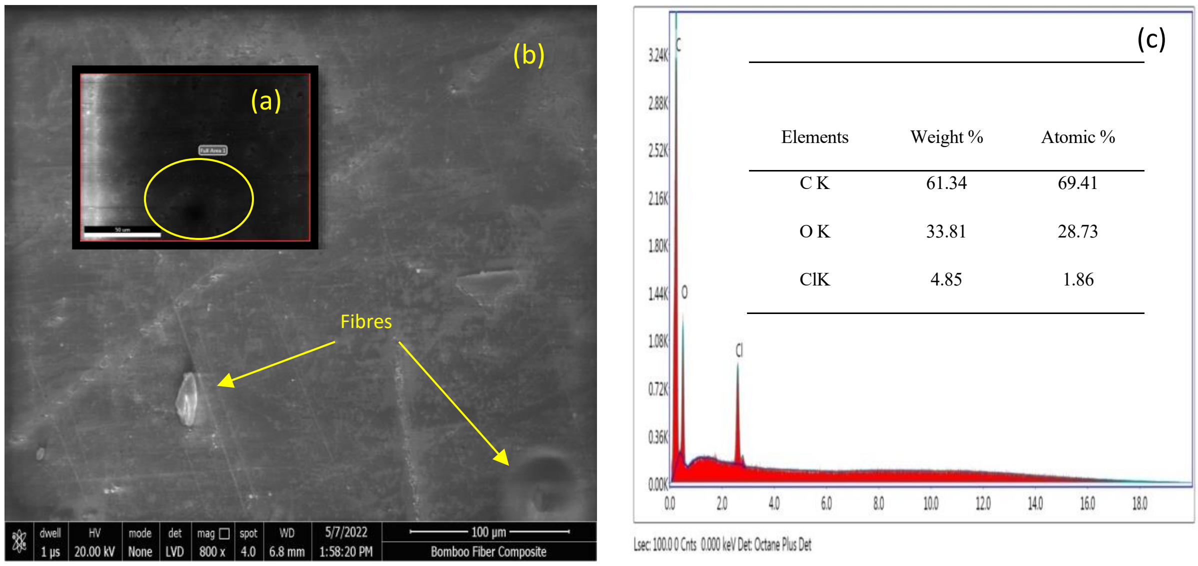

Fig 5. SEM-EDX images of composite for elemental composition.

Further review of the literature revealed that the treatment of fibers also plays an important role in the formulation of mechanical properties [35, 36]. The results observed by Rajeshkumar, Hariharan [35] and Yan, Chouw [36] findings suggest that treated fibers improve the mechanical properties of composites; as a result, the authors have initiated additional research to investigate this aspect. As an outcome, the average tensile strength of composites made of epoxy, untreated bamboo fiber

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reinforced, and treated bamboo fiber reinforced was evaluated three times. The graph in Figure 6 demonstrates that the tensile strength of alkali-treated fiber composites is considerably greater than that of untreated bamboo fiber-reinforced composites. As the percentage of alkali solution increases, the tensile strength also increases, and as a result, the composite of bamboo fibers treated with a 15% NaOH solution exhibits significant improvement compared to the composite of epoxy and untreated fibers.

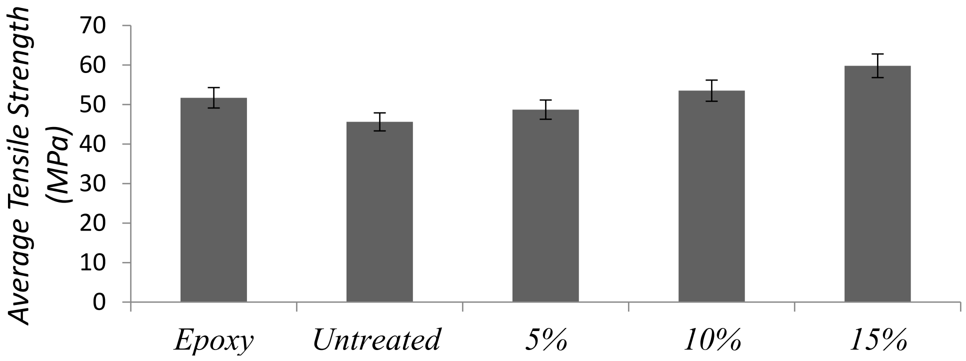

Fig 6. Average tensile strength of the epoxy, untreated and treated bamboo fibre composite materials.

The results of Rockwell hardness testing were comparable. As depicted in Figure 7, increasing the NaOH% concentration enhances the hardness of treated bamboo fiber-reinforced composites, with a composite containing 15% NaOH providing approximately 53 RHN. However, this is still somewhat inferior to epoxy. In contrast, untreated bamboo fiber-reinforced composite samples have the lowest RHN compared to other samples. Nonetheless, it is preferable to the 32 RHN hardness of bamboo-reinforced composite samples prepared exclusively by hand during the initial investigations. This demonstrates that modifying the fabrication procedure substantially enhances the composites' mechanical properties.

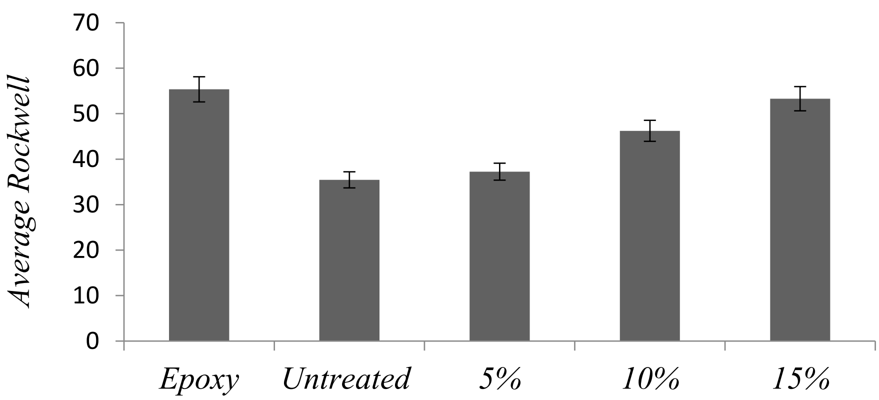

Fig 7. Average Rockwell hardness of the epoxy, untreated and treated bamboo fiber composite materials.

Figure 8 displays the results of the % elongation at break test, and it is evident that alkali treatment has no effect on the overall results. The percentage elongation at break of composites treated with 5%, 10%, and 15% NaOH concentrations does not differ significantly. Nonetheless, a significant increase in % elongation at break of the untreated fiber composite compared to the initial experiments (i.e., 2.6%) was observed. Again, this demonstrates that modifying the fabrication process can enhance mechanical properties.

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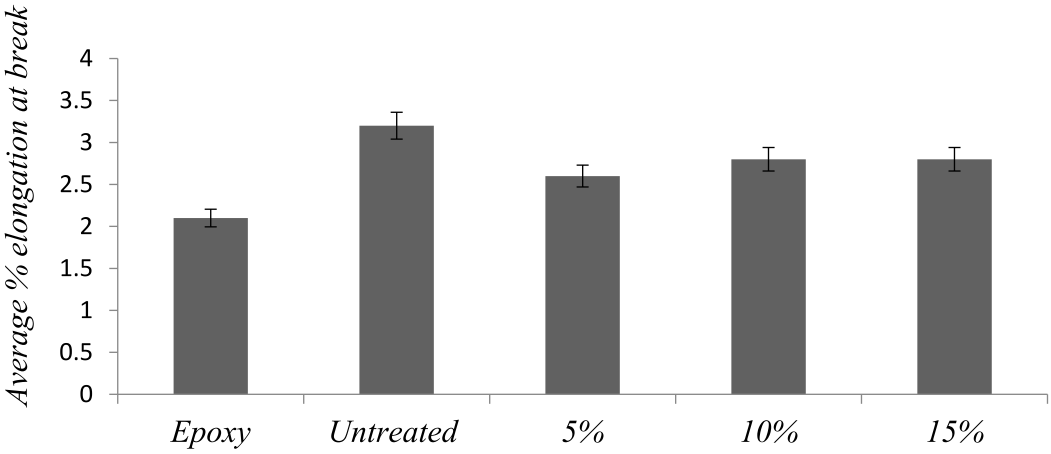

Fig 8. % elongation at break of the epoxy, untreated and treated bamboo fiber composites

The disruption of hydrogen bonds on the surface of the fiber caused by an alkaline treatment increases roughness. This treatment eliminates a portion of the lignin, wax, and lubricants that cover the fiber cell wall's exterior, depolymerizes cellulose, and exposes the crystalline phase. The formation of alkoxide is promoted by the addition of sodium hydroxide to natural fibers [39]. The fiber containing significantly more hydrogen clusters would be more cohesive with the epoxy matrix. Thus, alkaline processing has a direct effect on cellulosic fibrils, polymerization degrees, and the extraction of lignin and hemicellulosic compounds [40]. This improves the mechanical properties by strengthening the bond between the epoxy and bamboo fiber. In addition, the NaOH treatment induced hollow structure contraction, which tends to produce a stiffer fiber [41]. This has a negative effect on elongation at break, as reflected by the percentage elongation of chemically treated composites versus untreated composites. However, as shown in Figures 6 and 7, this substantially enhances the material's hardness and tensile strength.

4. CONCLUSION

When the ultimate tensile strength required is lower than 40 MPa, green composites made from bamboo fiber reinforced polymer matrices are among the best options. With a RHN of 68.2, glass fiber reinforced composites are harder than bamboo fiber composites. However, the decline in mechanical properties of bamboo fiber reinforced composites is attributed to the manufacture, curing process, and uneven distribution of fibers. To investigate the impact of alkali treatment on the mechanical properties of bamboo fiber composites, the authors conducted supplementary experiments with a modified manufacturing process and fibers treated with 5%, 10%, and 15% NaOH. When comparing the final study results to the preliminary study results, the researchers concluded that adjusting the fabrication method significantly improved mechanical attributes including tensile strength, hardness, and percentage elongation at break. There are advantages and disadvantages to treating composite fibers with alkali. As a result of the treatment, the composite's tensile strength increased to 59 MPa, and its hardness increased to 53 RHN, while the composite's % elongation at break remained unchanged at 2.8%.

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