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Mechanical Characteristics of Bamboo Nanofibers Reinforced with Carbon Nanotubes via Direct Chemical Treatment of Recycled Polypropylene

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Bamboo fibers, Polypropylene, CNTs, bamboo polymer composites, Direct Nitric Acid Hydrogen Peroxide treatment

Abstract

Bamboo was recognized for its economic potential and historical significance in construction was being investigated focusing on its fiber as a green alternative to traditional construction materials in response to limited resources in developing countries like Malaysia. Effects of different bamboo fibers mass fraction in bamboo polymer composites (0%, 10%, 20%, and 30%) on the BF/PP/CNTs composites' mechanical characteristics were assessed. Direct Nitric Acid Hydrogen Peroxide treatment was applied on bamboo fibers to remove lignin and hemicellulose. Employing CNTs as nanofiller in bamboo polymer composites was believed to result in better dispersion. Addition of waste Polypropylene in the composites able to reduce plastic waste crisis while making its strength properties to good use. The mechanical tests revealed significant increment in tensile and flexural properties up to 20% bamboo fibers mass fraction. However, beyond the value (20% BF) in the composites, the mechanical properties of composites declined, making the composites with 20% BF became the optimum value of bamboo fibers content. Thus, this indicates BF/PP/CNTs compositions had resulted in significant improvement in the mechanical properties using treated bamboo fiber and addition of CNTs.

1. Introduction

Malaysia as one of the developing countries is always being encouraged to utilize existing resources optimally for the resources to last for a long term as the price of construction materials keep increasing due to the limited resources supply. Therefore, the urge for new green construction materials exploration exists to be the substitute for conventional materials. Bamboo, a new evolving material considered as a great potential of economy. Bamboo as structural members has been traditionally used for hundreds of years in India, the Philippines, Latin America and China. Structural members made of bamboo have been used in construction platforms, long-span roofs, and low-rise houses. Not only that, it can also be implemented for demolition, civil works and decoration [2]. Through the advancement in technology era and high market demand, bamboo's usage has been extended to industrial applications and household product purposes [1].

On the other hand, natural fibers have been used as composite reinforcement, which has attracted the interest of many researchers [3]. Natural fibers can be obtained from animals, plants, or minerals. However, greater attention is given to plant fibers such as kenaf, sisal, mengkuang, jute, and bamboo for structural applications [4] because of their sustainability and availability. From previous studies, direct Nitric Acid Hydrogen Peroxide treatment was applied to bamboo fibers to extract lignocellulosic fibers by removing hemicellulose and lignin in order to enhance their properties [24].

Along with the mechanical performance of the final product from earlier research, fiber quality was also assessed following the extraction procedure. The tensile strength varied by about 800 MPa along the test span length, according to the results. 43 GPa is its average Young's modulus [25]. In addition, manufacturers and researchers have conducted a great deal of study on bamboo polymer composites (BPC). Bamboo is now available in a variety of forms, including fibers, woven mats, and blades that are combined with polymers.

Typically, the polymers are either thermosetting, like epoxy and polyester, or thermoplastic, like polyethylene and Polypropylene [5]. They are made for higher performance applications and are well-liked by researchers because to their eco-friendliness. In addition, even though polymer and bamboo fibers are inherently incompatible, fiber treatments or compatibilizing agents like sodium hydroxide (NaOH) or Polypropylene grafted with maleic anhydride (PPMA) can enhance the adhesion between the fiber and matrix and lower interfacial tension. Tensile, flexural, fatigue, and impact tests can be used to assess the improved mechanical behavior that these treatments are predicted to provide [26].

Furthermore, because of developments in nanotechnology, nanofillers have been widely employed in the field of nanocomposites. Because nanofillers come in a variety of particle sizes and diameters, they can significantly alter thermoset polymers' micromechanical behavior and give ultra-high reinforcement. The mechanical and physical characteristics of materials, including barrier performance, modulus, ablation resistance, and flammability resistance, are improved by the introduction of nanofillers. According to reports, these effects have been seen in epoxies even at modest filler concentration [7]. Usually, fillers are employed to improve the strength and stiffness of polymeric materials.

This is significant because blending polymers from different classes alone results in only a limited improvement in physical and mechanical properties, which is considered insufficient for engineering applications. However, high mechanical properties can be achieved if a high filler loading is employed, which increases cost and complicates the production process. Therefore, nanofillers were introduced, enabling high mechanical properties to be obtained with low filler content [6]. Consequently, in order to achieve better bamboo fiber quality with enhanced mechanical properties, suitable treatments combined with appropriate fillers and polymers are necessary.

The plastic waste issue has affected land and sea environments globally for decades with packaging, and construction are the primary contributors. Most packaging becomes waste within a year, in contrast to plastics from construction, they have a longer time of use before they become waste. Non-fibre plastic materials refer to plastic materials that do not have a fibrous or textile-like structure such as plastic packaging and plastic containers. It becomes worse as the discarding rate is higher compared to the recycling and incineration rate showing the waste is not managed effectively through environmentally friendly methods [8]. Malaysia was ranked eighth among 192 countries by the mass of mismanaged plastic waste in 2010 and further predicted by authors to be 1765977 tonnes in 2025 [9].

Since natural fibers, such as bamboo fibers, are hydrophilic due to the presence of hydroxyl groups, this leads to a reduction in the mechanical properties of the composites in which they are incorporated [10]. Therefore, according to a previous study [11], direct Nitric–Hydrogen Peroxide (NCHP) treatment was able to enhance the water resistance of bamboo fibers and improve their mechanical properties by achieving a high percentage of lignin and hemicellulose removal. However, these components were not completely removed, allowing water absorption, which results in a gradual decrease in the mechanical properties of bamboo over time.

According to [22], the study assessed epoxy composites incorporating treated and untreated short bamboo fibers. They point out that natural fibers are lightweight, low-cost, and eco-friendly alternatives compared to synthetic fibers. Mechanical properties, including tensile, flexural, and impact strength, improve with increasing fiber content. However, excessive fiber content can weaken the bond at the matrix–fiber interface. Treated fibers, particularly those treated with NaOH, demonstrate greater strength improvements due to better adhesion and stress transfer. The study concludes that fiber treatment, fiber–matrix bonding, orientation, and interfacial stress transfer are important factors in enhancing composite performance.

Research on 0.1% to 0.5% CNTs in bamboo and glass fiber hybrid composites revealed a decrease in tensile modulus for 0.3% and 0.5% CNT content, although it may increase tensile strength. In contrast to the 0% CNT composites, the flexural strength and modulus of the 0.1% CNT composites somewhat declined. Nevertheless, the flexural strength and modulus of composites containing 0.3% and 0.5% CNTs were significantly lower. The primary failure modes of the composites were found to be fiber pull-out and matrix cracking. The decrease in flexural strength of the composites was caused by the mismatched geometries of the CNTs and bamboo fibers in sustaining stresses [12].

Polypropylene-reinforced bamboo has been studied. The mechanical performance of PP/PS blends reinforced with bamboo fiber was examined by Tang et al. [13]. The addition of bamboo fiber up to 40 weight percent enhanced the adhesion in the PP/PS blends, as seen by the composites' increased tensile and flexural strength and modulus.

Polypropylene (PP) composites reinforced with twill-weave bamboo fabric were evaluated in another study [23]. When compared to pure PP, the study found notable increases in tensile strength, tensile modulus, flexural strength, flexural modulus, and impact strength. Effective stress transfer from the matrix to the fabric was credited with this improvement. Fiber characteristics, content, and orientation all affected the composite modulus. PP reinforced with bamboo showed improved impact resistance, rigidity, and load-bearing capacity. Additionally, slight increases in crystallinity and melting temperature were noted. Bamboo fabric has a significant favorable impact on the mechanical performance of PP composites, as evidenced by the further reduction of crack propagation caused by reinforcement.

Furthermore, according to previous research [14], tensile properties of bamboo reinforced with recycled Polypropylene were evaluated. The tensile strength of the composites increased up to 20% bamboo fiber mass fraction. The decline in tensile strength in composites with 30% bamboo fiber was attributed to voids formed between fiber arrangements in the composites. In this study, several compositions of bamboo fibers and Polypropylene at a constant CNT content were used to evaluate the mechanical properties of bamboo reinforced with Polypropylene and CNTs composites. Tensile and flexural tests were used to evaluate mechanical properties. This study offers insightful information for investigating eco-friendly building materials.

2. Research Methods

2.1 Preparation of Materials

One of the materials employed as a filler in the composites was semantan bamboo fibers. Bamboo powder with a particle size of 500 µm was obtained by cutting the fibers into shorter lengths of around 3 cm, grinding them in a machine, and sieving them. Conversely, Carbon Nanotubes (CNTs) functioned as nanofillers for reinforcement, while waste Polypropylene was used as the composite matrix.

For 48 hours at 50°C on a heated plate at 200 rpm, the bamboo powders were combined with 200 mL of 3.2 mol/L nitric acid and 90 mmol/g per 5 g of fiber using magnetic stirring [11]. This method of extracting lignocellulosic fibers is known as direct Nitric Acid–Hydrogen Peroxide (NCHP) treatment. After that, the mixture was cleaned with distilled water and filtered using a vacuum pump until the filtrate's pH was neutral. The bamboo fibers that had been filtered were dried at 50°C in an oven.

Polypropylene waste was gathered from trash cans near MARA University of Technology (UiTM) Shah Alam. Plastic drinking cups and plastic food containers marked with the plastic number five made comprised the waste Polypropylene used in this investigation. The garbage was immersed in boiling water and cleaned with soap and water to remove dirt and bacteria [15]. Before being employed, the collected Polypropylene waste was cleaned and its odor eliminated by a hygienization process. The gathered plastic food containers and drinking cups were carefully cleaned for at least 20 seconds using detergent and either warm or cold water to get rid of any dirt on the plastic's surface and eradicate any bacteria that might survive in many places and spread around. Only then, it can be crushed in a grinding machine to have finer sizes of Polypropylene. Figure 1 and Figure 2 show the sample of sieve bamboo and crushed Polypropylene.

Fig. 1 *Bamboo fibers after the sieving process*

Fig. 2 *Crushed Polypropylene used as the matrix material*

2.2 Composite Fabrication Process

The treated bamboo fibers were reinforced with Polypropylene (PP) and Carbon Nanotubes (CNTs). The BF, PP, and CNTs were melt-blended using an internal mixer at a temperature of 190°C and a constant speed of 50 rpm for 30 minutes to produce the composites, based on the composition presented in Table 1 [13]. The resulting composites were subsequently crushed (Figure 3) and hot-pressed at 170°C for 30 minutes, followed by cooling to approximately 30°C. All laboratory tests for the prepared samples (Figures 3 and 4) were conducted at the Material Strength Laboratory, School of Mechanical Engineering, Universiti Teknologi MARA (UiTM), Shah Alam.

Table 1 *Compositions of PP/Bamboo fiber/CNTs samples*

Sample Designation	CNTs (wt%)	PP/Bamboo fiber (99.9wt%)	
		Bamboo fiber (wt%)	PP (wt%)
PP/BF 0	0.1	0	100
PP/BF 10	0.1	10	90
PP/BF 20	0.1	20	80
PP/BF 30	0.1	30	70

Fig. 3 *Composites after the crushing process*

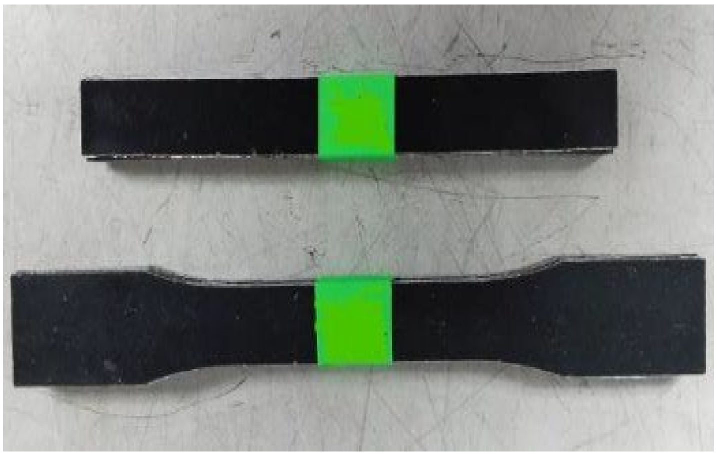

Fig. 4 *Hot-pressed Polypropylene composite samples*

2.3 Lab Testing for Mechanical Properties

Tensile tests were performed on four samples where each sample consisted of three specimens using the Shimadzu Servopulser tensile testing machine referring to [16]. This standard is suitable for assessing tensile properties of reinforced and unreinforced plastics including composite materials produced from Polypropylene and bamboo fibers. The test was conducted through a thin flat strip sample which was mounted in the grips of a testing machine with increasing load in tension. Three specimens were tested for each sample to obtain the average of the three specimens' tensile properties for each sample. Each specimen was in the form of Type I dog bone-shaped in size following the standard which was 13 mm wide, 3 mm thick and 165 mm long. Standard procedures for conditioning before samples were tested referring to [21] which states that specimens should be conditioned for 40 hours at 23°C and 50% relative humidity. The setup speed for testing was 2 mm/min with a 50 mm gauge length.

In addition, flexural tests were also conducted to assess the mechanical properties of thecomposites using the Shimadzu Servopulser flexural testing machine referring to [17]. This standard is suitable to be used to assess the flexural characteristics of both reinforced and unreinforced plastics which includes high modulus composites and electrical insulating materials. The testing was conducted using a three-point loading system that applied force to a simply supported beam (specimen). This test was done on three specimens for each sample where the size of each specimen was 13 mm wide, 3 mm thick and 127 mm long in rectangular cross-section form. Standard procedures for conditioning before samples were tested referring to [21] which states that specimens should be conditioned for 40 hours at 23°C and 50% relative humidity. All the samples should be ensured to have proper air circulation around them by placing them in suitable racks, suspending them from metal clips, or laying them on wide-mesh wire screen frames to prevent the samples from any moisture retention or heat buildup which could affect the accuracy of test results. The setup speed for the crosshead was 2 mm/min with a 60 mm load span and each sample was tested using a Shimadzu Servopulser Flexural Testing Machine which was shown in Figure 5 and Figure 6.

Fig. 5 *Tensile testing of Polypropylene-based composite samples*

Fig. 6 *Flexural testing of Polypropylene-based composite samples*

3. Result and Discussion

3.1 Tensile Properties

As shown in Figure 7, the difference in BF and PP content had a significant impact on the tensile parameters, specifically tensile strength and tensile modulus. Consistent with the results reported in [14], both characteristics increased with BF inclusion up to 20%, after which a drop was seen at 30% BF concentration. The composite with 20% BF had the highest tensile modulus (1082.30 MPa) and tensile strength (12.948 MPa). The sample without BF (0%), on the other hand, had the lowest values, with a tensile modulus of 803.74 MPa and a tensile strength of 7.284 MPa.

According to earlier research by [12], insufficient dispersion of nanofillers within the PP matrix was the cause of the decrease in tensile strength at increased BF loading. Particle entanglement probably caused nanofiller aggregation in the composite containing 30% BF and 0.1% CNTs. Increasing the fiber concentration decreases the distance between the fibers and the Polypropylene matrix, which restricts the matrix's capacity to adequately penetrate and encapsulate the fibers, as documented in [13]. The interfacial connection between the fiber and matrix is weakened as a result of inadequate wetting. As a result, the efficiency of stress transfer from the matrix to the fibers decreases. The 20% BF formulation produced the best tensile performance because effective stress transfer is necessary to fully use the fibers' reinforcing capacity.

Additionally, once the maximal tensile strength was attained, the specimens showed necking behavior, which is characterized by elongation and a decrease in cross-sectional area [14]. The material's ability to support loads was diminished by this area reduction, which ultimately caused the necked section to fracture. Tensile strength and modulus were still greater than those of the 0% BF sample, despite a declining trend in the tensile characteristics of the 30% BF composition. The 30% BF composition maintained reasonably high mechanical performance despite the drop, as evidenced by the relatively minor divergence from the optimal values. Overall, the findings demonstrate the reinforcing efficacy of BF in the BF/PP/CNTs composite system by indicating that an ideal BF level is necessary to maximize tensile characteristics.

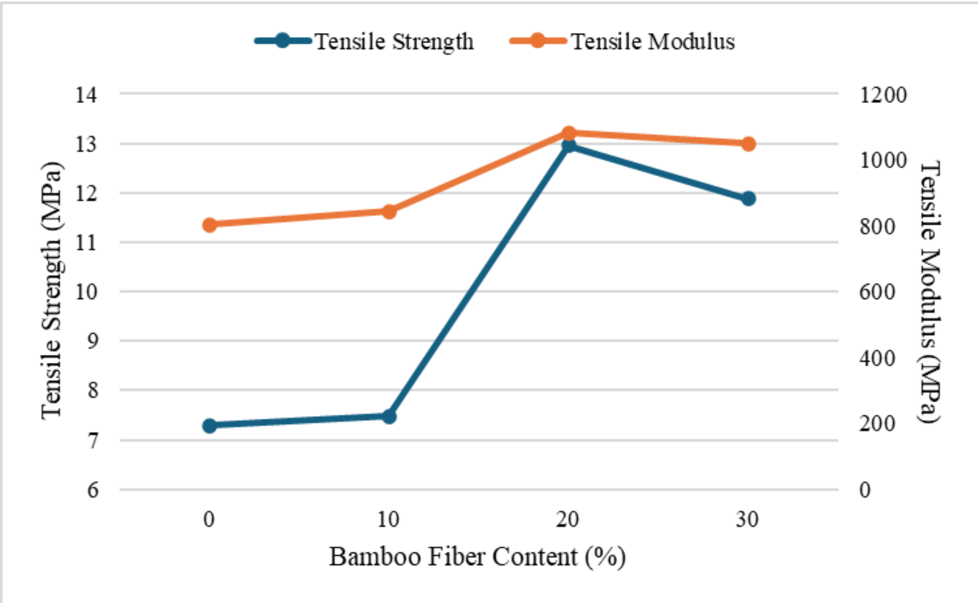

Fig. 7 *Variation of tensile properties of bamboo polymer composites with different bamboo fiber contents*

3.2 Flexural Properties

Flexural strength and flexural modulus were two further mechanical attributes assessed in this investigation. Both characteristics often improved as the composites' BF content increased, as seen in Figure 8. In comparison to the composite without BF, this shows that the addition of BF improved the flexural performance. Before exhibiting a declining tendency at 30% BF level, the flexural strength improved up to 20% BF content.

On the other hand, despite the decrease in flexural strength, the flexural modulus increased even at 30% BF, reaching its maximum value of 1935.40 MPa. Because these reinforcements have a higher modulus than the matrix material, [18] states that adding fillers or fibers to a polymer matrix usually increases composite stiffness. However, a high filler or fiber content can lead to weak interfacial bonding and stress concentration, which lowers flexural strength.

According to earlier studies, the ideal CNT content is roughly 0.5% [12]. The same study's results, however, also showed a decline in flexural performance at this level. Because it showed much higher tensile and flexural performance than other CNT concentrations, 0.1% CNTs was chosen as a constant parameter in this investigation. According to the current findings, adding 0.1% CNTs had no negative impact on the mechanical characteristics' improvement as the BF content increased.

Additionally, at 59.627 MPa, the composite containing 20% BF showed the greatest flexural strength. Flexural performance was improved as a result of improved fiber-matrix adhesion brought about by an increase in BF content. Stronger bonding and effective load transmission were encouraged by the interphase region between the fiber and matrix, which functioned as a compatibilizing layer. Because of this, the composites were able to absorb more strain energy before breaking [13].

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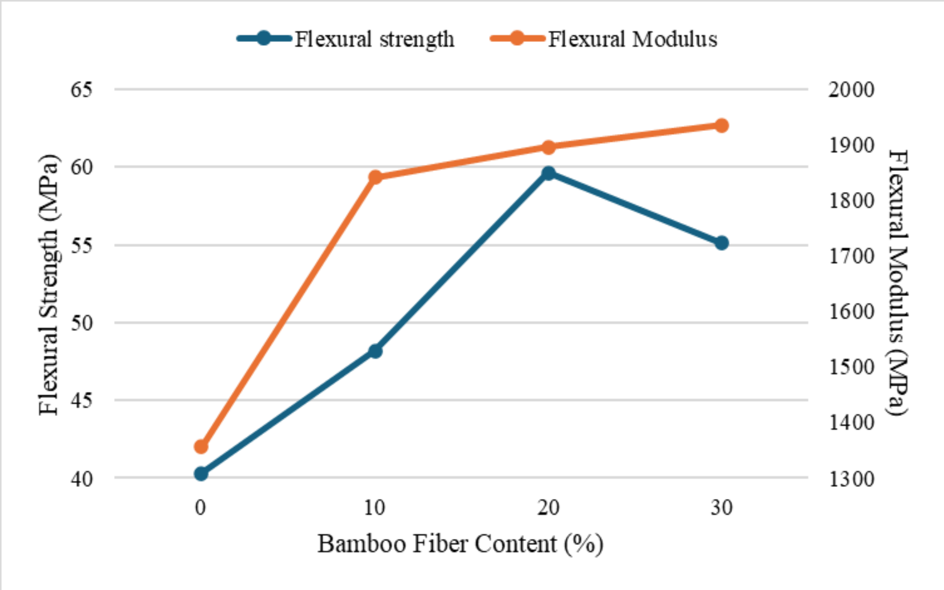

Fig. 8 *Effect of bamboo fiber content on the flexural properties of bamboo polymer composites*

3.3 Comparison between Tensile and Flexural Properties

Figure 9 compares the tensile and flexural strengths as the BF content increases. As the BF content rose from 0% to 20%, both attributes significantly improved. Furthermore, the related tensile strength values were consistently lower than the flexural strength values. The strengthening effect of bamboo fibers is responsible for this improvement. The type of loading used determines how these attributes differ from one another. While flexural strength indicates the material's resistance to bending loads, tensile strength indicates the material's capacity to tolerate axial pulling pressures.

According to [19], fibers' orientation and dispersion within the matrix, which facilitate effective load transfer and energy absorption under bending conditions as opposed to tensile loading, make them generally more successful in enhancing flexural performance. 20% BF was found to have the highest tensile and flexural strength values, suggesting that this composition is the ideal fiber percentage for bamboo polymer composites.

Additionally, Figure 10 shows how adding BF up to 20% increases the tensile and flexural modulus. Tensile modulus values were consistently lower than flexural modulus values. This behavior is explained by fibers' propensity to align in a way that offers more resistance to bending than to stretching [19].

While flexural modulus indicates the material's stiffness under bending conditions, tensile modulus describes how much a material deforms under tensile pressure. A high flexural modulus implies that the material is robust and able to preserve its structural integrity under bending loads, whereas a high tensile modulus shows that the composite is stiff and shows little elongation under tensile stress. Note that there is no straight proportionality between modulus and strength. Higher modulus might lead to increased brittleness even though it enhances stiffness. This is due to the fact that materials with high stiffness typically have a limited capacity for deformation before failing, which can result in decreased tensile and flexural strength when fracture happens before significant deformation [20].

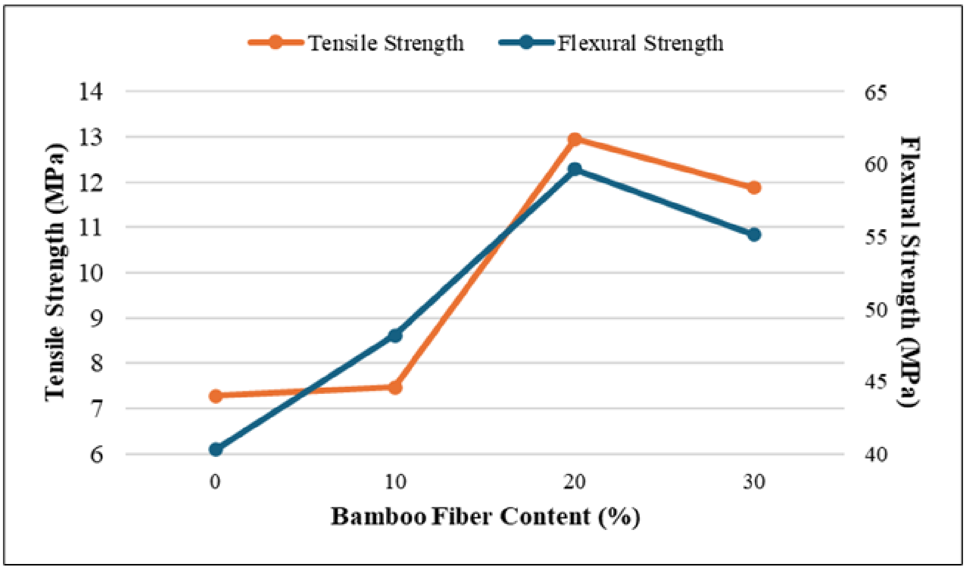

Fig. 9 *Effect of bamboo fiber content on the tensile and flexural strength of bamboo polymer composites*

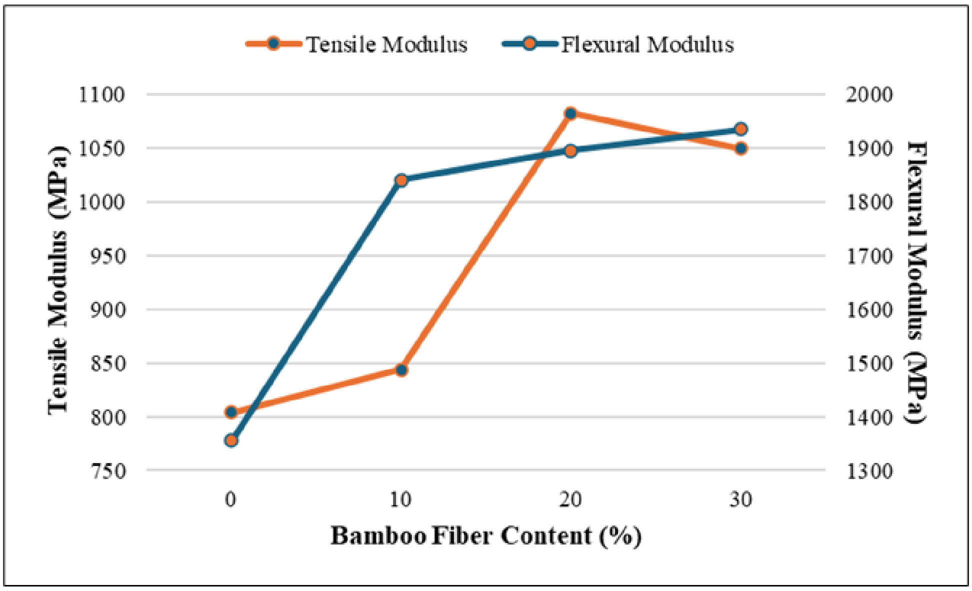

Fig. 10 *Effect of bamboo fiber content on the tensile and flexural modulus of bamboo polymer composites*

4. Conclusion

This study emphasizes the potential of bamboo fibers as a sustainable substitute for traditional building materials, especially in light of rising costs and scarce resources. Because of its adaptability and good mechanical performance, bamboo has long been used in construction applications.

In order to improve the mechanical performance of Bamboo Polymer Composites (BPC), this study assessed the tensile and flexural behavior of Semantan bamboo fiber reinforced with Polypropylene and Carbon Nanotubes (CNTs). Untreated bamboo fiber's inherent drawbacks, especially its hydrophilic nature, were also discussed because they could have a detrimental effect on the material's mechanical performance. When paired with polymer matrices and Carbon Nanotubes (CNTs), Nitric Acid Hydrogen Peroxide (NCHP) treatment was found to efficiently reduce lignin and hemicellulose content, enhancing overall mechanical performance and water resistance.

This study also looked at plastic garbage, which is still a major environmental problem in Malaysia. By encouraging the use of plastic-based materials in value-added applications, the addition of Polypropylene to the BPC system helps sustainability initiatives in addition to improving mechanical qualities.

The testing findings showed that adding up to 20% of bamboo fibers greatly improved the material's tensile and flexural qualities. In comparison to those without fiber reinforcement, the composites showed greater strength and modulus. However, because of dispersion and interfacial bonding constraints, a decrease in tensile strength was noted with increased fiber concentration. On the other hand, flexural characteristics improved as the fiber content increased, demonstrating how well bamboo fibers work to increase the composite structure's stiffness and rigidity.

Overall, by incorporating renewable resources and tackling the problems associated with plastic waste, this work advances the creation of sustainable building materials. The results show that bamboo fiber reinforced composites supported by Polypropylene and Carbon Nanotubes have the potential to be a practical way to enhance material performance and advance environmental sustainability.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Nur Iwana Irdina Othman, Nur Ilya Farhana Md Noh, Suffiyana Akhbar, Zakiah Ahmad;* ***data collection:*** *Nur Iwana Irdina binti Othman, Nur Ilya Farhana Md Noh, Suffiyana Akhbar;* ***analysis and interpretation of results:*** *Nur Iwana Irdina binti Othman, Nur Ilya Farhana Md Noh, Suffiyana Akhbar, Zakiah Ahmad;* ***Technical editing and data verification:*** *Rahida Wati Sharudin, Sajith Thottabthil AbdulRahman, Bijesh Paul, Lum Wei Chen, Norshariza Mohamad Bhkari, JL Ng;* ***Writing review & critical revision:*** *Ruzaimah Razman, Mohamad Azim Bin Mohammad Azmi, Salihah Surol, Deprizon Syamsunur, Anis Azmi. All authors reviewed the results and approved the final version of the manuscript.*

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