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Functionally Graded Natural Fibre and SiC-reinforced Polymer Composite: Mechanical Properties

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Abstract

Multifunctional materials, also called functionally graded materials (FGMs), are based on natural fibres or fillers and vary in composition and/or microstructure to control functional, structural, or thermal, properties. Functionally graded materials (FGMs) have been created for use in spacecraft, aircraft, and other engineering applications because they can withstand extremely high temperatures. Particle-reinforced FGMs, which make up the majority of FGMs, are made differently depending on their position. The mechanical and physical characteristics of epoxy composites reinforced with bamboo fibre were examined in the current study. Short bamboo fibre composites were created using a range of layer densities and four different fibre loadings. Few properties have been found to significantly increase as a function of fibre loading, but others, like void fraction, increase from 1.68% to 5.77%. Epoxy composites reinforced with bamboo fibre are added silicon carbide (SiC) filler at weight percentages of 0, 10, 15, and 20 while maintaining the same fibre loading (40 weight percentage). In addition to improving other mechanical properties, this decreases the void fraction. The substance can enhance performance while preserving the natural world's equilibrium. The quantity of layers affects both flexural and tensile strength. By adding bamboo fibre as a particulate filler to epoxy composites, a high-strength, lightweight composite material could be produced. The interactions between the fibre and matrix were investigated using SEM.

Keywords: Composites, Tensile Test, Flexural Test, Impact Test, SEM, FGMC

INTRODUCTION

Two crucial words are contained in the phrase "functionally graded materials": "functionally" and "graded." Grading is modified by the word "functionally." These include both basic functional materials and graded materials. Materials with differentiated functions within them are the general definition of functionally graded materials. The term "FGMs" refers to functionally graded materials moving forward. The first FGMs were one-body materials with a gradual change in the thermal expansion coefficient between the front and back sides. This was accomplished by switching their metallic composition for ceramic. FGMs were designed to reduce internal thermal stress at high temperatures.

Additionally, it is possible to achieve the desired qualities of graded structures by gradually changing the density, level, texturizing, grain size, structure, chemical composition, and other physical properties layer by layer [1]. You can do this to give graded structures the qualities you want. Furthermore, in order to improve overall efficiency and address environmental concerns, recent studies have concentrated on figuring out how to incorporate the necessary properties into functionally graded composite materials [2]. Researchers think that natural fibres and fillers are

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a better choice for use as a reinforcement for graded composite in light of this. They are used as an alternative to synthetic filler and fibres like metallic, carbon, semi-crystal aramid, and other materials that are similar because they have good mechanical properties, are environmentally friendly, and can be recycled. The primary components of hemp, bamboo, sisal, kenaf, banana, coconut coir, and other natural fillers and fibres are hemicelluloses, cellulose, and lignin [3–7]. One of the best materials for use as a reinforcement in a polymer matrix is thought to be bamboo because it is a rapidly growing plant that is widely available. It is also referred to as natural glass fibre because its mechanical properties are comparable to those of other synthetic fibres [8].

There are a lot of advantages to having this instead when compared to homogeneous materials. Nevertheless, unless it was capable of competing commercially with the homogeneous ceramic components that are already on the market there wouldn't be much point in developing such a FGM material [9]. The processing of FGMs can be done using a wide variety of methods; therefore, it is essential to match the appropriate method with the appropriate application. As a direct consequence of this, a sizeable portion of this paper is dedicated to discussing the testing of FGM, in particular for FGMs that are performed in bulk [10].

It will also produce residual stresses that will have an effect on the mechanical properties, as the gradient composition in FGMs is not an only result in a spatial variation in properties. These residual stresses will have an impact on the mechanical properties. The positive impact that compressive residual surface stresses can have on a material's strength as well as its resistance to wear is one of the potential advantages of using FG components [11–13]. As is demonstrated in this paper, the gradient has to have the right kind of design in order to achieve the ideal kind of distribution of the residual stresses. Applications of structural FGM that are carried out in environments with challenging operating conditions will be given special consideration. In order to determine how the number of layers and the speed of the crosshead movement affect the material's stiffness and strength, at three different crosshead speeds, the composite samples are put through a tensile test. Producing the three distinct composite samples requires adjusting both the total number of layers and the density of each individual layer (five, four, and four). A three-point bend test is one method that can be used to determine the flexural strength and modulus of a material.

MATERIALS SPECIFICATION

Epoxy hardener known as HV 953 IN and adhesive resin known as AW106 make up the selected epoxy matrix. HV 953 IN is an epoxy-based hardener, and AW106 is an adhesive resin. The matrix material is made up of thermosetting polymers that are a member of the epoxide family, and the reinforcement phase is made up of bamboo fillers that have a density of 0.45 grams per cubic centimetre. Epoxy was chosen as the material to serve as the matrix because it has a higher tensile strength and modulus than any other option.

In this particular investigation, a form of reinforcement called short bamboo fibre that was obtained from a location in close proximity was used. Epoxy resin and hardener are both products that are distributed to Ciba Geigy India Ltd.'s clientele (LY 556). Because of the numerous advantages that they provide, epoxy resins are used extensively in the production of a wide variety of cutting-edge composites [14]. This is due to the fact that these resins are available. These benefits include superior mechanical and electrical properties, excellent adhesion to a diverse range of fibres, and good performance even when exposed to high temperatures [15–16]. A supplier in the nearby area has silicon carbide (SiC) in the 85 m range that is available for purchase. Moulds used in the production of composites typically consist of stainless steel and have dimensions of 225 millimetres on each side and 45 millimetres in volume.

A straightforward mechanical stirring procedure is utilised in the process of combining epoxy resin, short bamboo fibre, and SiC particles. After that, the mixture is poured into various moulds so that it can be characterised and tested in accordance with the requirements of the various testing conditions and standards. Samples of composite materials with a variety of different compositions can be created either with or without the use of a filler. The precise constituents of the composites that were manufactured for the purpose of this investigation are outlined in Table 1. After the composite material has been allowed to dry, a releasing agent is applied to make it easier to remove it from the mould. Any trapped air bubbles are carefully released using a sliding roller before the mould is sealed and cured at a temperature of 35°C for 24 hours at a constant pressure of 15 kg/cm^2 for the duration of the curing process. After the curing process, the specimens are then cut down to the appropriate sizes in order to undergo mechanical testing. The unfilled bamboo epoxy composites have been given the designations EB-1 for Epoxy + 0 weight percentage Bamboo Fibre, EB-2 for Epoxy + 10 weight percentage Bamboo Fibre, EB-3 for Epoxy + 20 weight percentage Bamboo Fibre, and EB-4 for Epoxy + 30 weight percentage Bamboo Fibre. These designations refer to the weight percentage of bamboo fibre in the epoxy. Assigning the designations EBS-1 for epoxy with 40 weight percent bamboo fibre and 0 weight percent SiC, EBS-2 for epoxy with 40 weight percent bamboo fibre and 10 weight percent SiC, EBS-3 for epoxy with 40 weight percent bamboo fibre and 15 weight percent SiC, and EBS-4 for epoxy with 40 weight percent bamboo fibre and 20 weight percent SiC to bamboo epoxy composites with SiC in order to develop specimens is possible.

Table 1. Theoretical and experimental densities of bamboo epoxy composites without SiC and with SiC along with void fraction

Designation	**EB-1**	**EB-2**	**EB-3**	**EB-4**	**EBS-1**	**EBS-2**	**EBS-3**	**EBS-4**
Experimental Density	1.18	1.19	1.20	1.19	1.17	1.29	1.42	1.48
Theoretical Density	1.19	1.23	1.26	1.32	1.23	1.38	1.51	1.67
Void Fraction (%)	1.68	3.56	4.78	5.87	5.77	3.24	4.78	8.05

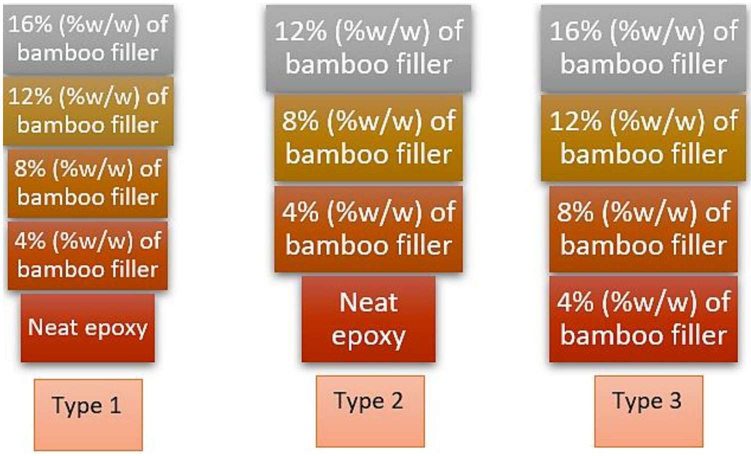


Figure 1. A representation in schematic form of a stepwise graded composite sample.

The rectangular and dumbbell tensile and flexural test specimens are created by using the hand layup technique. A mould made of silicone rubber is fabricated with the required dimensions, and this process is carried out in accordance with the applicable ASTM standards. The thermoset epoxy resin AW106 and the corresponding hardener HV 953 IN are first combined in a ratio of 10:8, as directed by the manufacturer. Next, the required quantity of filler is added, and the mixture is continued to be stirred with the assistance of a mechanical stirrer to ensure that it is thoroughly combined. After that, the mixture is added into the silicone rubber mould one layer at a time, with each successive layer containing 4 weight percent more filler weight than the one before it. In order to ensure that the layers are properly levelled, a roller is moved over them at regular intervals, and there is a time gap of three hours between each successive layer. As can be seen in Figure 1, preparations are being made for the examination of three distinct types of samples: Type I, Type II, and Type III. These samples, respectively, have five, four, and four layers. The first layer of FGCM was applied, after the previous layer had been allowed to cure for four hours. This ensured that there would be adequate adhesion between the layers. The Type I specimen is made up of five layers, with the bottom layer being made of epoxy in its purest form and the top layer containing bamboo filler at a weight-to-weight ratio of 4%. The following three layers are prepared by adding 8, 12, and 16% (% weight/volume) of bamboo filler, respectively.

The Type II specimen is made up of four layers: an epoxy layer is located at the bottom, followed by layers of bamboo filler containing 4, 8, and 12% (% weight/weight), respectively. The Type III mattress has four layers, and the percentage of bamboo filler in each layer after the first increases to 16% from 4%, 8%, and 12% respectively. This results in a total of 16 percent of bamboo filler in the mattress.

There is a total of 0.75, 0.54, and 0.90 grams of bamboo filler in each individual example of Type I, Type II, and Type III, respectively. Both Type II and Type III have four layers, but the amounts of filler that are distributed throughout each layer are different. After the application of all of the layers has been completed, the functionally graded composite specimens are subjected to a post-curing process in which they are cured further by being kept in a muffle furnace at a temperature of seventy degrees Celsius.

EXPERIMENTAL DETAILS

The standard model can be used to estimate the weight fraction density of composite materials. A 20 N diamond printer with a square base and faces that are 136° apart is used to press the sample. In line with ASTM D3039-76, the samples are put through a tough tension test. The flexural strength of composites can be measured in many ways, such as with the Instron 1195 three-point bend test. A 10.2-millimeter-deep notch is used for impact tests on composite samples. ASTM D 256 says that a battery of impact tests is done on composite specimens by an impact tester. These tests are done on the samples.

Using a tabletop Universal testing machine (UTM) with a 50 kN load cell capacity, the tensile test is carried out in accordance with ASTM D638-02aTYPEI conditions of 18°C and 50% relative humidity. The repeatability of each of the three types of specimens' five samples is evaluated for each of the four crosshead speeds—5, 100, 250, and 500 mm/min. The fixture holds the standard specimen in place at both of its ends and is made to stretch the specimen longitudinally until it snaps. The tensile strength of a material can be calculated using the equation that follows.

$$\text{Tensile strength, } \sigma = \frac{P_{max}}{bh}$$

P_{max} is the maximum load in Newtons, MPa is the pressure, mm is the specimen's width, and h is the specimen's thickness (mm).

ASTM D790-03 calls for three-point flexural tests using a 50 kN tabletop UTM at 30 °C and 50% relative humidity. The Type I specimen is tested twice: once with 0% and 16% as the top and bottom layers, and once with 16% and 0%. Figure 2 shows how the other two samples are tested. All three types of specimens have higher layer filler percentages on the top and bottom to create top and bottom sides.

During a three-point flexural test, the specimen is held in place over an 80-millimetre span and is put under a point force that is increasing at a rate of 2.13 millimetres per minute until it breaks. The equation for bending strength can be found below.

$$\text{Flexural Strength, } \sigma = \frac{3P_{max}L}{2bh^2}$$

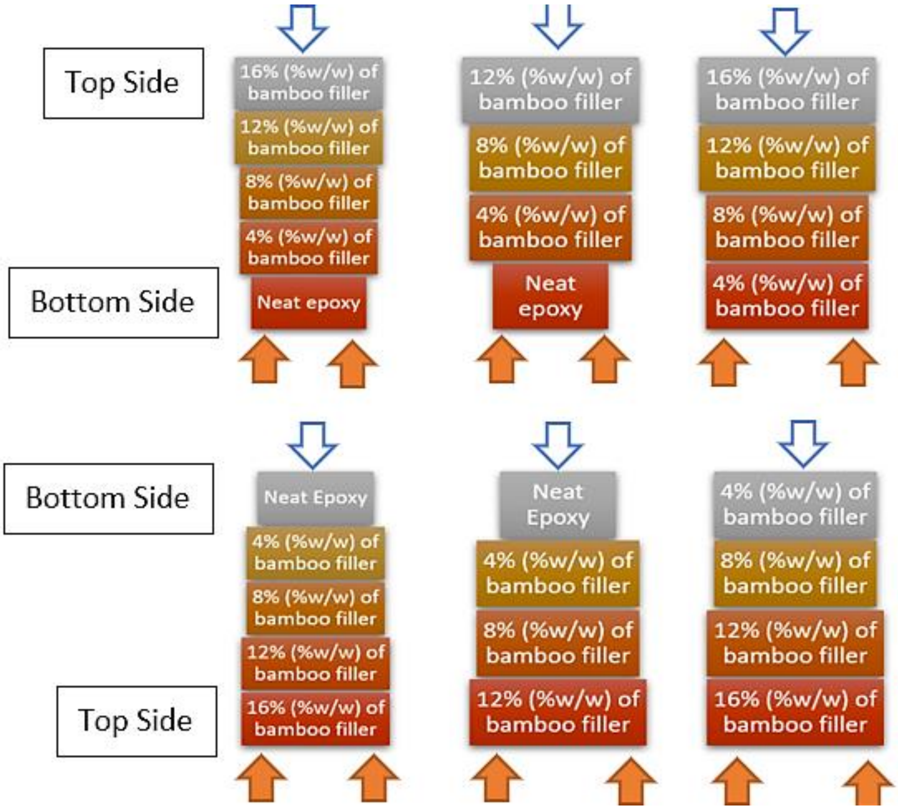


Figure 2. Three-point flexural test configuration.

P_{max} is the maximum load at failure (N) and is measured in MPa, where L is the support span (80 mm), b is the width (mm), and h is the thickness (mm) (mm).

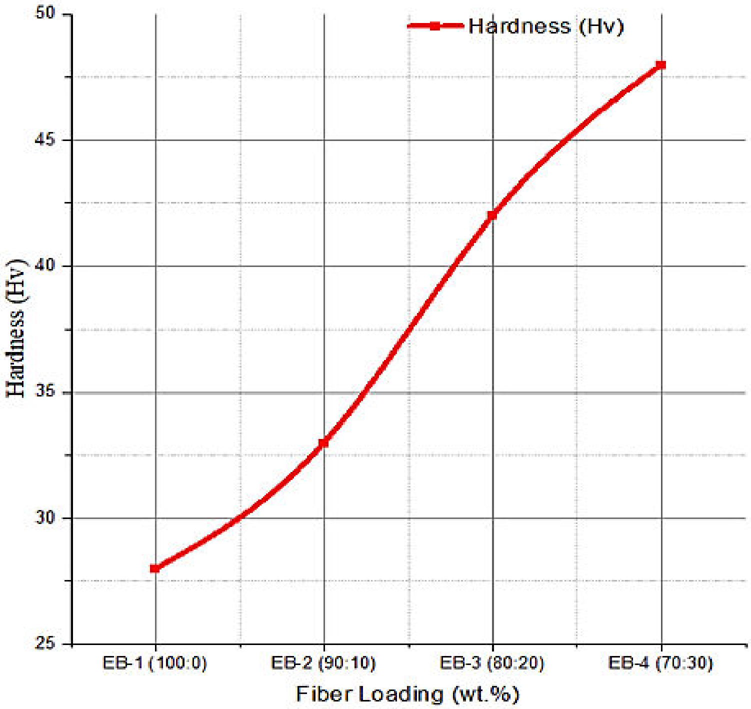
The morphological analysis of the composite surface is performed using a JEOL JSM-6480LV SEM analysis. Using a JEOL sputter ion coater, the samples are painstakingly cleaned, allowed to air dry, and then coated with 100 layers of thick platinum. A 20 kV SEM is then used to examine the samples. Platinum is vaporised under vacuum and then applied to the composite samples in order to increase their conductivity.

RESULTS AND DISCUSSION

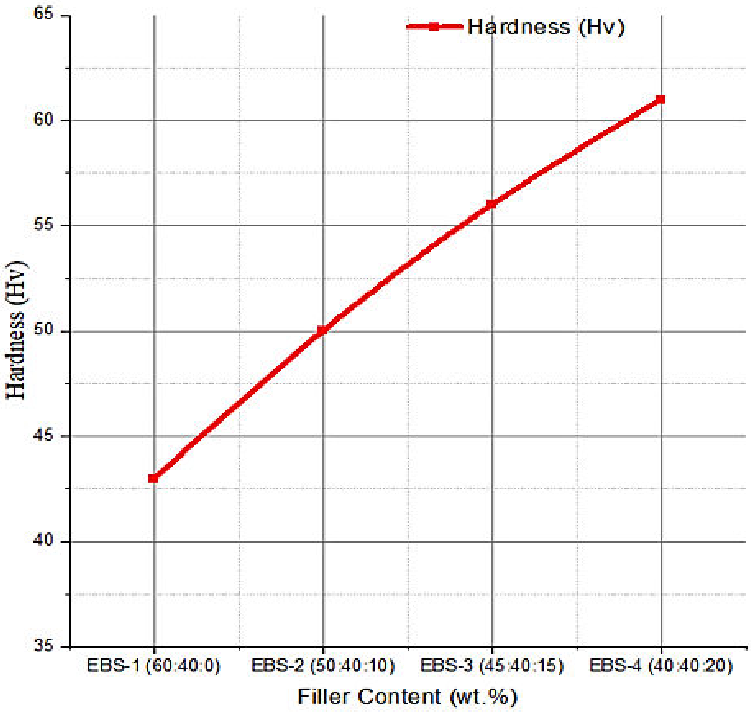
Figure 3 (a) depicts how the loading of fibres affects the hardness of composites. The test results show that as the fibre loading is increased, there is a significant increase in the hardness of epoxy composites reinforced with short bamboo fibres. The addition of SiC to the bamboo epoxy composites, as seen in Figure 3 (b), causes the hardness of the composites to rise even higher in comparison to the composites that aren't filled with anything.

The percentage of ceramic filler in the material contributes directly to the material's apparent level of hardness. This is to be expected in terms of bamboo's hardness, as bamboo fibre exhibits a significantly higher level of hardness compared to the soft polymer matrix in which it is embedded. When the wear properties of such systems are evaluated, taking this into consideration should be important. In point of fact, the values of hardness are a measure of the better wear resistance. This is due to the fact that hard materials are better able to resist friction and wear.

In Figure 4 (a), it is demonstrated that the weight fraction of the fibre has a variety of effects on the composite's tensile strength. For the first time, the tensile strength of composites can reach up to 10.21 MPa when the weight fraction of fibre is increased to 40 weight percentage. The tensile properties measured in this work are very comparable to those measured by a large number of researchers who came before, despite the fact that the process of extracting bamboo fibres is different. Figure 4 (b) shows the connection between the amount of filler and the tensile strength of bamboo epoxy composites. Without a doubt, the tensile properties of the bamboo epoxy composites were significantly improved by the addition of SiC particles. Tensile strength increases noticeably up to a content of 10% SiC by weight; however, as SiC is added in larger amounts, the strength begins to decline, as shown in Figure 4. (b).



(a)



(b)

Figure 3. (a) Impact of fibre loading on the hardness of composite materials (b) Impact of filler content on the hardness of composites.

The bamboo fibres have a higher tensile strength as a result of the epoxy resin's capacity to transmit and distribute the applied stress. The composite is therefore more resilient to failure than unfilled composites when subjected to heavier loads. The cross-linking network that forms between the fibres and the polymer matrix containing the filler is what causes the increase in tensile strength. Regardless of filler content, the tensile strength begins to decline with a rise in filler content above 10% weight percent.

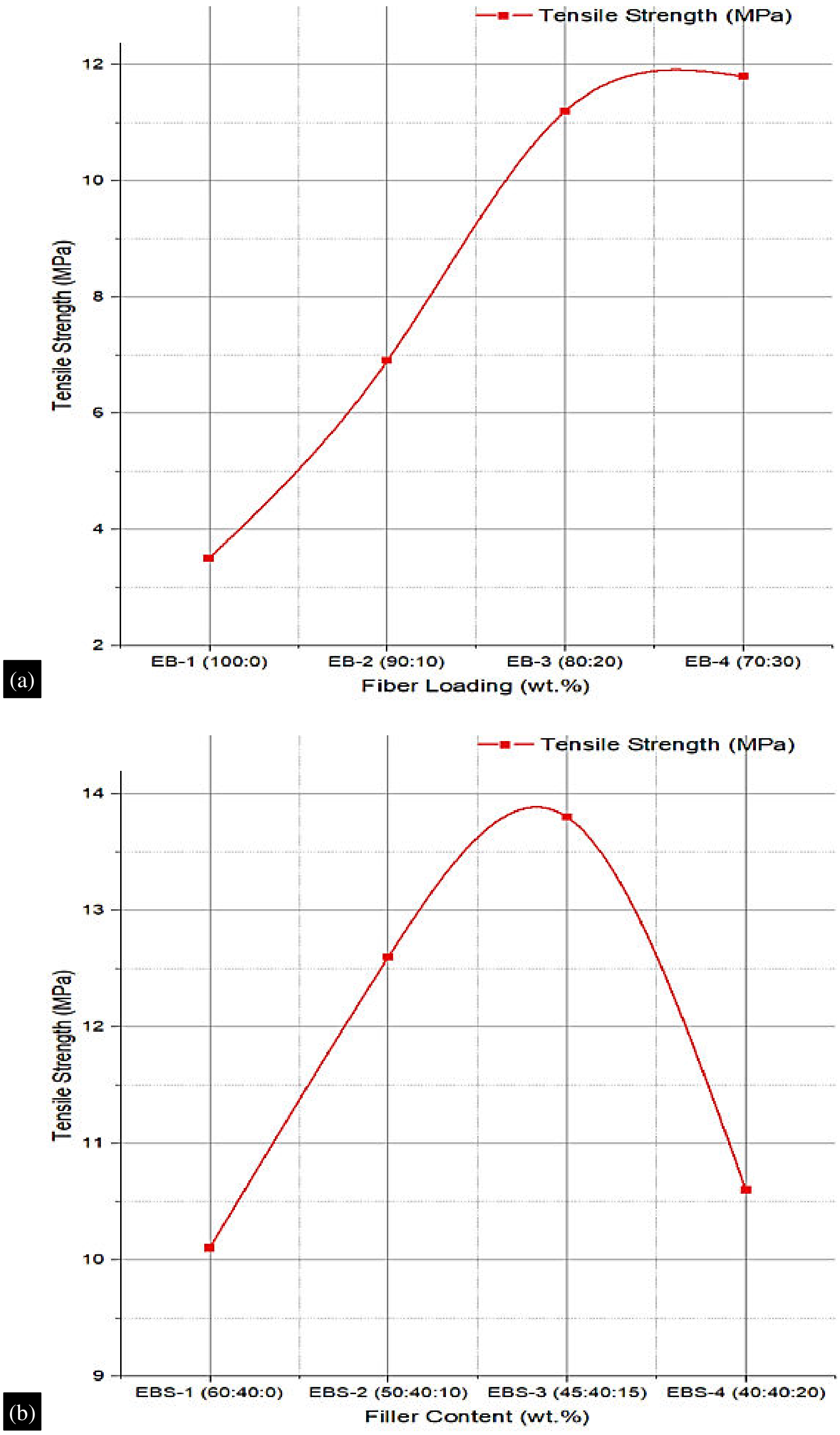


Figure 4. Composite tensile strength vs. fibre loading vs. filler content.

The tensile test provides the most important details regarding how the material responds with respect to uniaxial loading. The relationships between the crosshead movement speed and the Young's modulus, strain at break (or tensile strain), and ultimate tensile strength are depicted in Figures 5, 6, and 7, respectively, for Types I, II, and III. The final result is computed using the load-elongation curve, which is the main outcome of the tensile test. At different speeds, the maximum tensile stress values for each specimen are 21.785, 26.385, and 29.584 MPa.

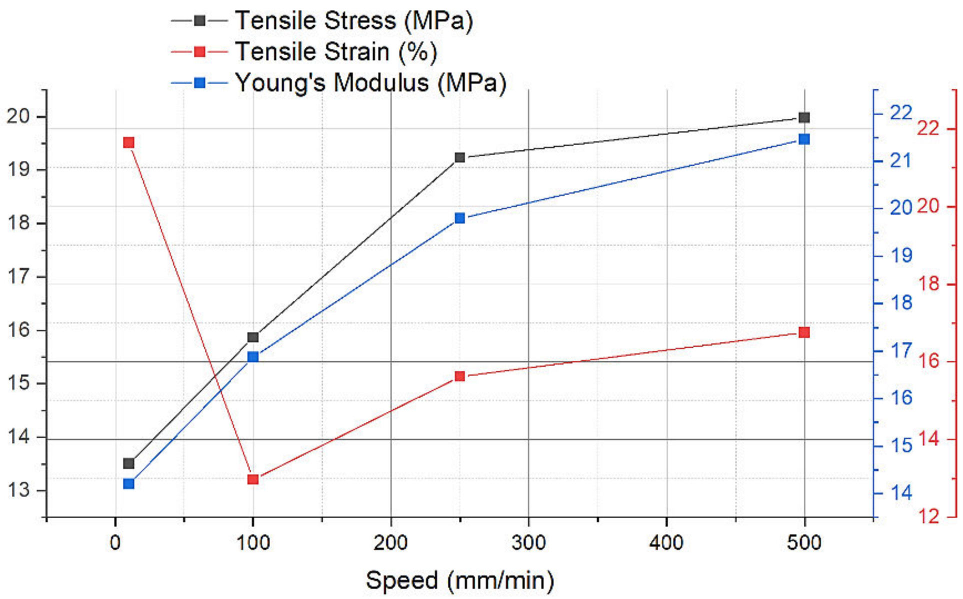


Figure 5. Functionally graded Type I composite tensile properties.

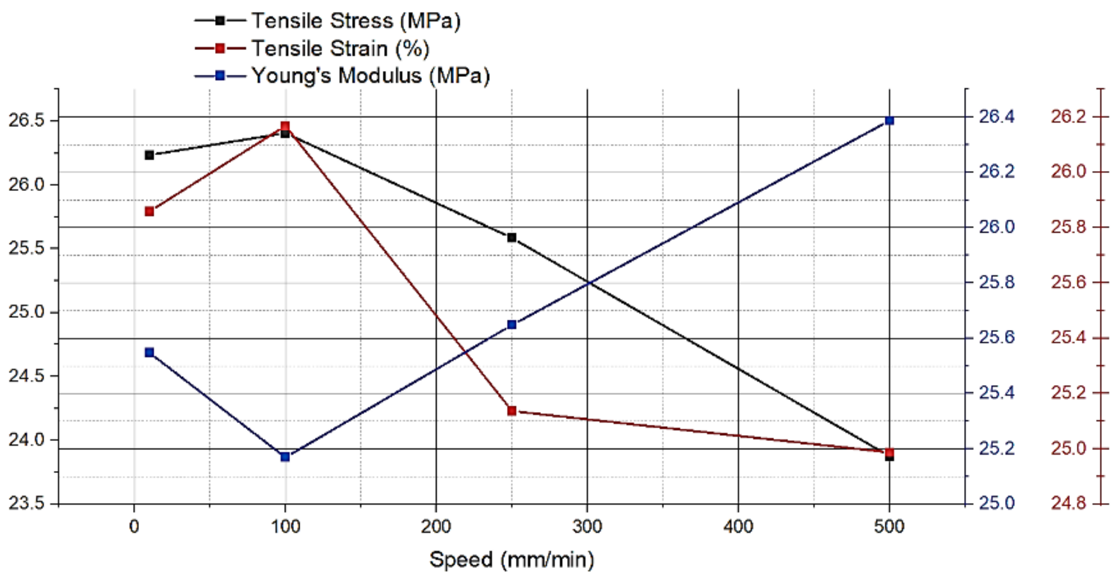


Figure 6. Function-graded tensile composite material sample Type II.

Young's modulus has maximum and minimum values of 29.74 and 13.585 MPa, respectively, at 100 and 5 mm/min. At speeds of 5 and 500 mm/min, respectively, the ultimate tensile stress is reached and is 29.87 and 27.56 MPa. The Young's modulus has maximum and minimum values of 23.875 and 13.685 MPa, respectively, at 100 and 5 mm/min. The strength and modulus values are significantly influenced by the matrix and reinforcing phase. In composites, the matrix material is always present around the fillers, which are short fibres that assume a cylindrical shape. At 5 and 100 mm/min, tensile strain has maximum and minimum values of 7.87% and 6.32%, respectively.

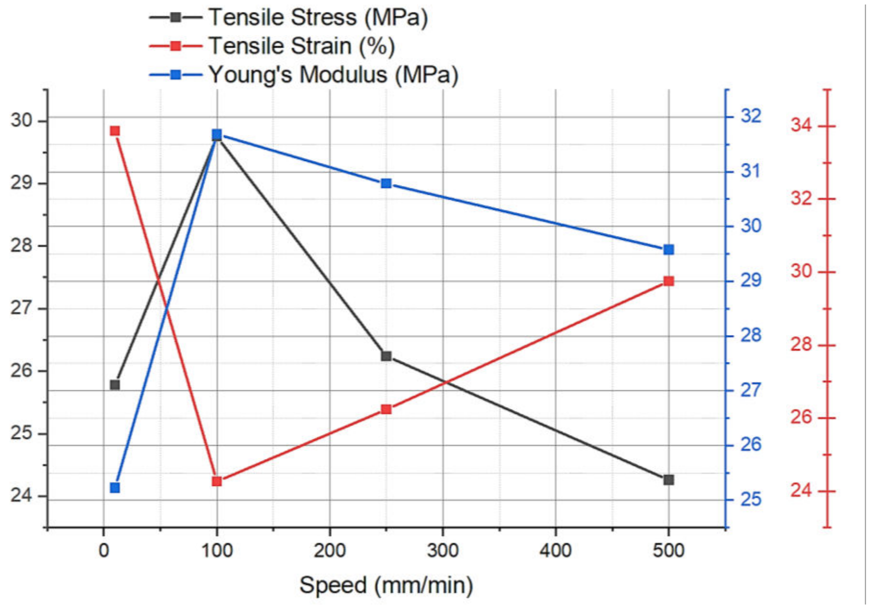
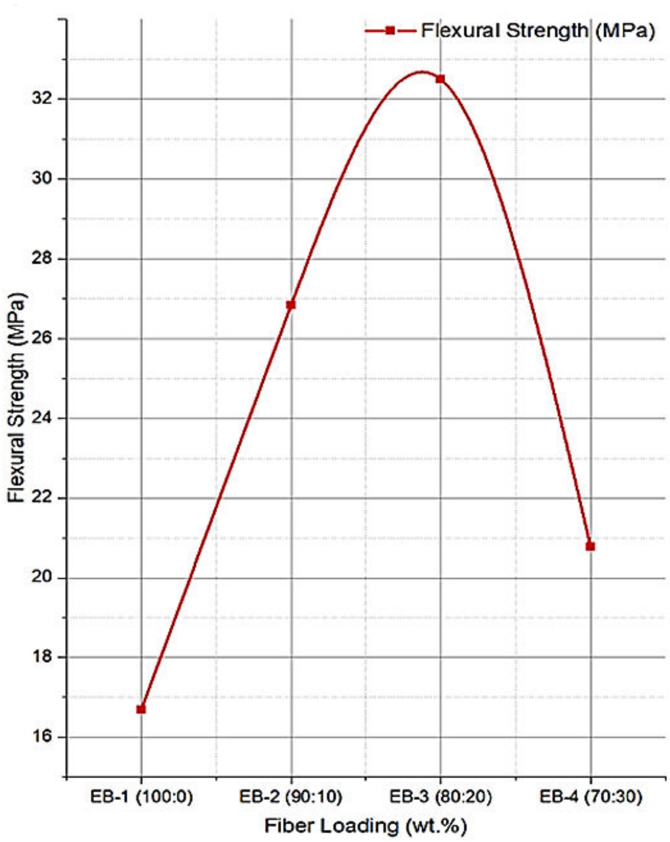
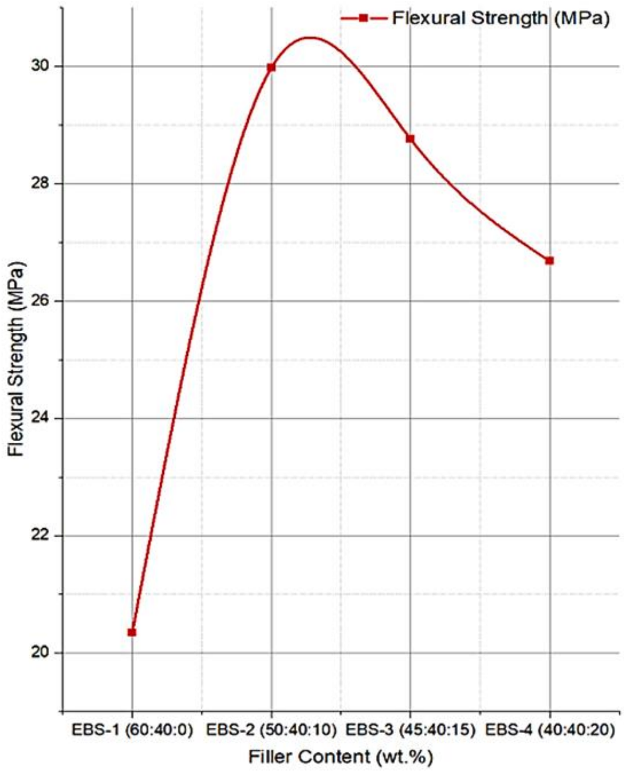


Figure 7. Functionally graded composite Type III tensile properties.

The flexural strength of composites is affected by fibre loading, as shown in Figure 8(a). Flexural strength increased along with the increase in fibre loading up to 30 weight percent. This is a consequence of the bamboo composite's enhanced matrix-to-fibre adhesion and elevated flexural stiffness. However, the SiC-added bamboo epoxy composites' bending strength only increases by about 15 weight percent before it begins to decrease more than the unfilled one (See Figure 8 (b)). The lack of interfacial bonding may be attributed to the incompatibility of bamboo fibre, SiC particles, and the epoxy matrix.



(a)



(b)

Figure 8. (a) Composites' flexural strength as a function of fibre loading (b) Composites' flexural strength and filler content.

Figures 9, 10, and 11 show how composite specimens of types I, II, and III vary in terms of their flexural properties. According to Fig. 9, the top side of a type I sample's flexural stress values is 49.5 MPa, while the bottom side is 47 MPa. Flexural strength and bending modulus are the three-point bend test's two most significant results. Figure 10 displays the variation in flexural strain for the bottom and top sides of each kind of composite sample. Flexural strain measurements for type I samples show values of 0.119 GPa and 0.094 GPa, respectively. Figure 11 illustrates how materials with more filler weight revealed the flexural modulus values. The evidence suggests that each type of graded composite has a higher top side flexural strain due to the presence of a denser filler. While the flexural modulus for type I samples can be determined to be 1.413 and 1.37 GPa, respectively, from both the top and bottom sides.

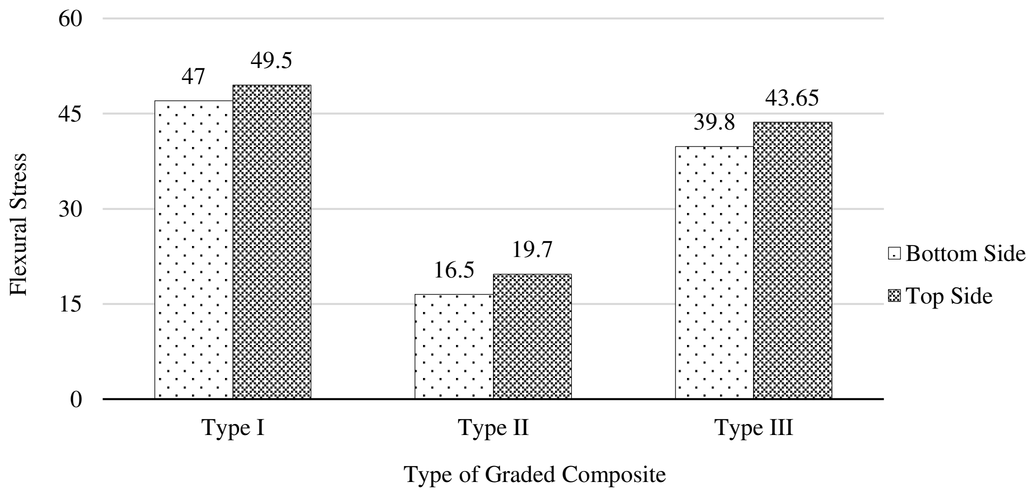


Figure 9. Functionally graded composite sample flexural stress.

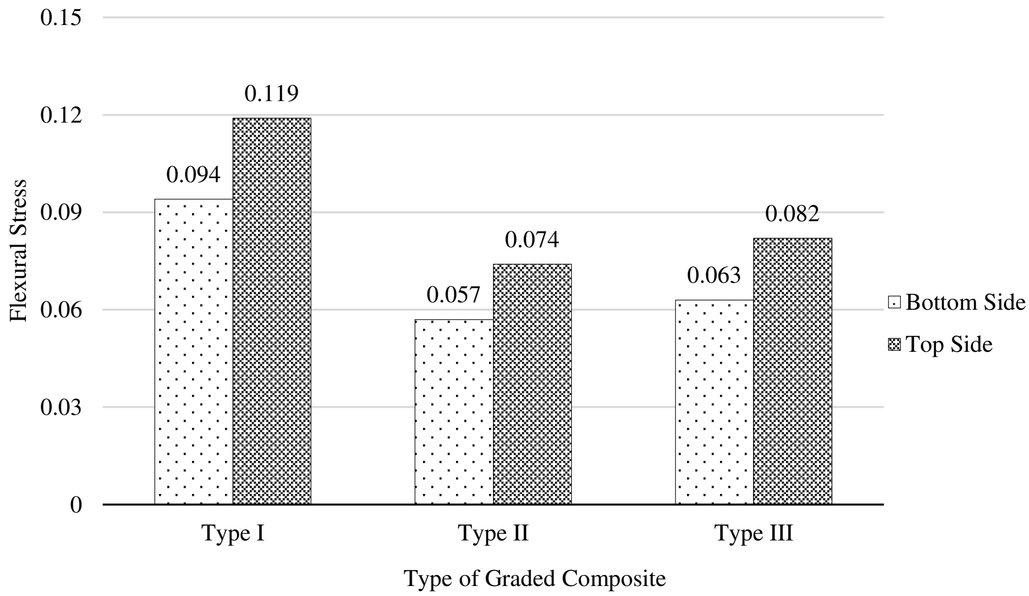


Figure 10. Composite material flexing under functional strain grading

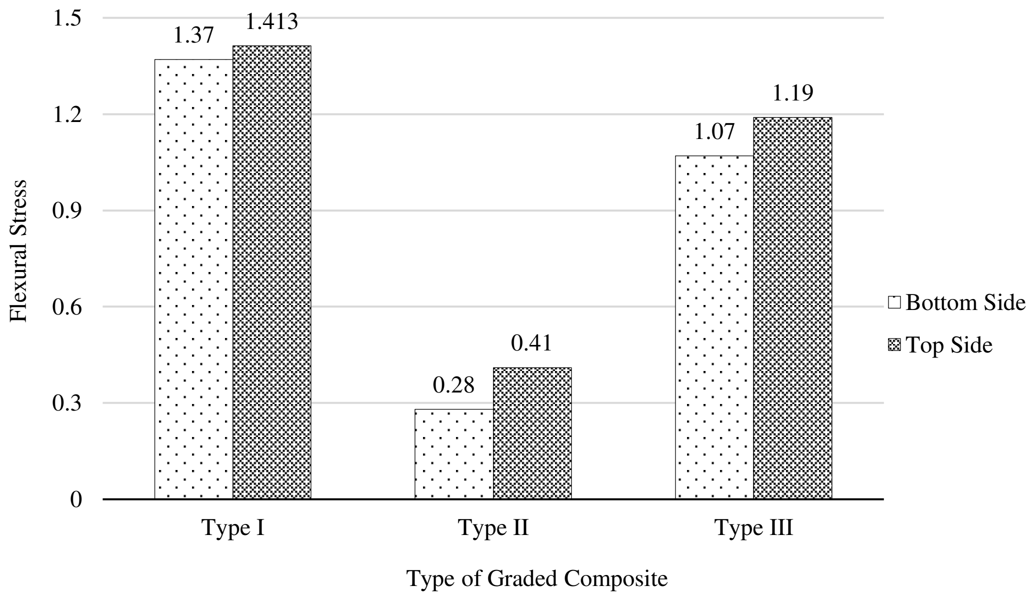
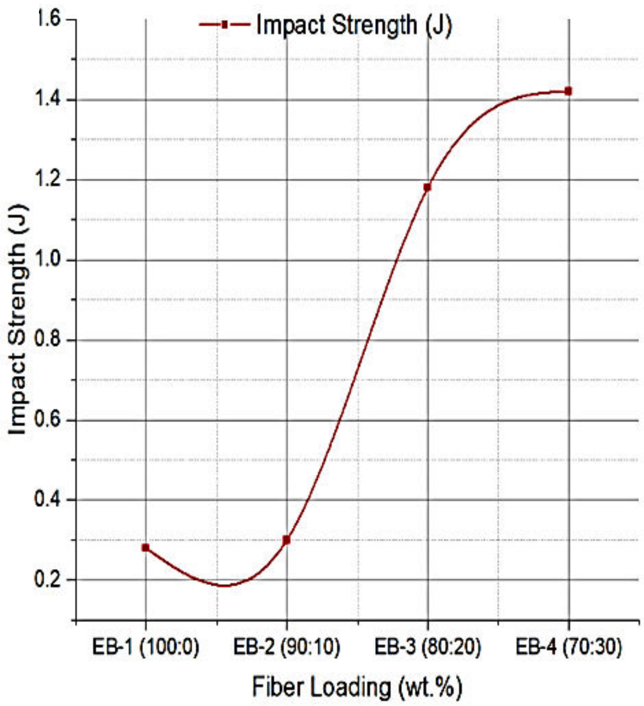


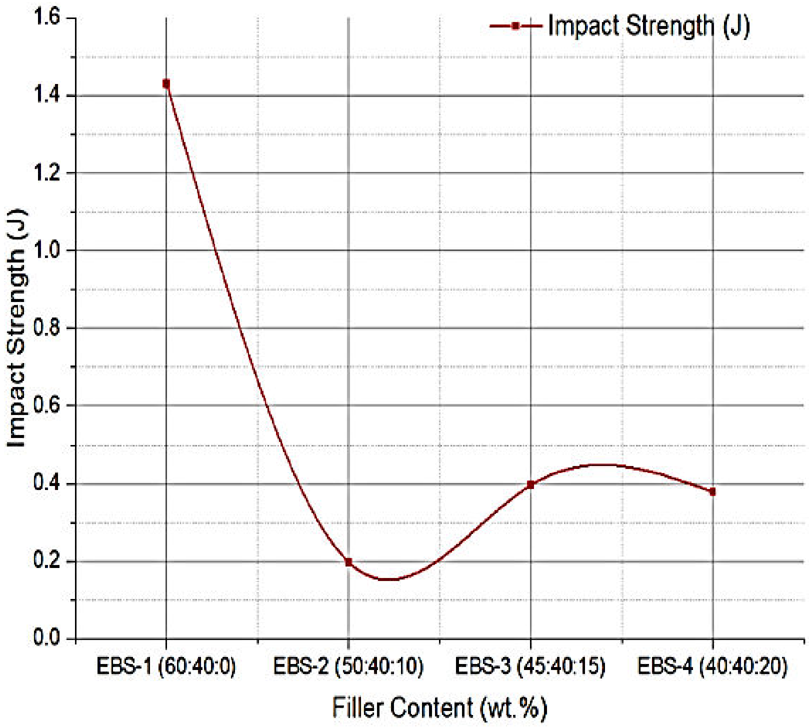
Figure 11. Modulus of flexibility for a composite material with varying degrees of functionality.

The highest flexural strength continues to be found in type I samples when compared to type II and type III samples. The strength of the specimen weakens as the filler percentage on its topmost side decreases when tested in reverse. Due to loading-related delamination, no specimen failed the test, and the failure mode shows little to no filler out. In today's composite materials, flexural strength consistently increases with the number of layers.

The overall toughness of composite materials is directly correlated with its impact properties. Fibre reinforced polymer composites are primarily used in structural applications. When an impact occurs, numerous micro cracks are created as a result of the micro-spaces that were created between the fibre and matrix polymer, which reduces the impact strength of the composites as shown in Figure 12 (a) & (b). Similar to unfilled bamboo epoxy composites, particulate filled bamboo epoxy composites experience dramatic reductions in impact strength up to a certain filler percentage before experiencing an increase.



(a)



(b)

Figure 12. (a) Fibre loading modifies composites' impact resistance (b) Composite impact strength vs. filler content.

Figure 13 (a) & (b) depicts the fracture surfaces analysis of the short bamboo fibre reinforced epoxy composite before and after the tensile test. When tensile load is applied to the fibre, the fractured surface of the composite exhibits' matrix material breaking under initial loading conditions. The fibre modifies the crack's course and directs it along the fibre's surface. When the crack front crosses the fibre/matrix interface, it causes fibre debonding, a sign that the matrix has separated around the fibres, and fibre pull-out.

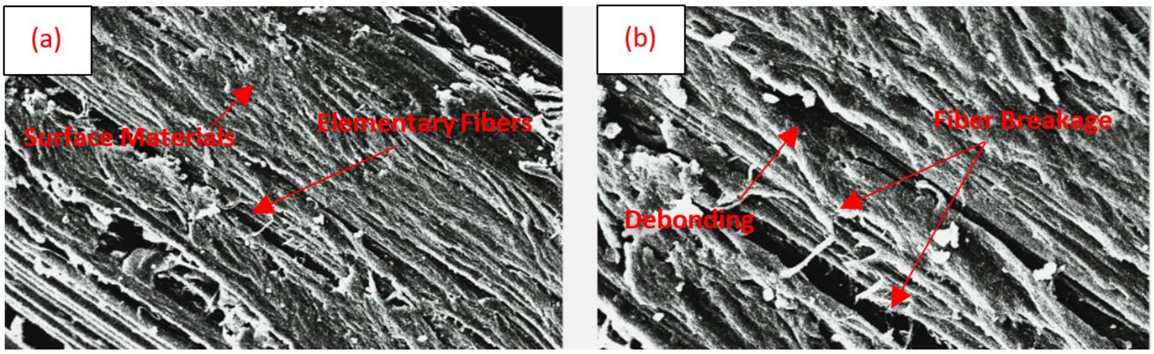


Figure 13. SEM images of bamboo-reinforced epoxy composites (a) before and (b) after tensile testing.

CONCLUSION

The following findings emerged from an investigation into the impact of fibre loading (bamboo fibre) on the mechanical and physical behaviour of short fibre reinforced epoxy composites. The investigation was carried out experimentally.

- A new category of hybrid composites based on epoxy and reinforced with short bamboo fibres is an example of a successful area of research and development.
- With an increase in fibre loading, certain properties, such as the void fraction, have been observed to rise from 1.68% to 5.77%.
- Silicon carbide (SiC) filler is added to epoxy composites reinforced with bamboo fibre at weight percentages of 0%, 10%, 15%, and 20% to decrease the void fraction and increase the hardness and other mechanical properties, while holding the fibre loading constant at 40%.
- It is noted that there have been significant improvements in the following properties: hardness (from 44.32 to 62.37 Hv at 20 weight percentage SiC filled), tensile strength (10.032 to 12.693 MPa for 15 weight percentage SiC), flexural strength (21.687 to 29.932 MPa for 10 weight percentage SiC), and void fraction (5.77 to 3.24 % for 10 weight percentage SiC).
- After a tensile test, the epoxy composite reinforced with short bamboo fibres will undergo an analysis of its fracture surfaces. Development and examination of flexural and tensile properties of functionally graded epoxy composite with bamboo filler reinforcement was carried in this work.
- Tensile properties are studied by varying the crosshead's movement speed to understand the relationship between Young's modulus, tensile strength and strain rate. Producing a functionally graded polymer composite with bamboo filler by hand has proven to be a viable option for creating eco-friendly, biodegradable materials.
- The tensile properties (strength and modulus) are found to improve with increasing crosshead speed. Type I specimen at 500 mm/min, Young's modulus is found to be 21.489 MPa, while at 100 mm/min maximum tensile strength is found to be 29.785 MPa type III specimen.

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