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Optimization of Tailor-Made Natural- and Synthetic-Fiber-Reinforced Epoxy-Based Composites for Lightweight Structural Applications

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Abstract: Natural and synthetic fibers offer a multitude of advantages within the automotive sector, primarily due to their lightweight properties, including appealing characteristics such as adequate mechanical strength, low density, improved acoustic–thermal insulation, cost-effectiveness, and ready availability. In this study, we aimed to strengthen epoxy-based composites with natural and synthetic fibers using bamboo and glass, respectively. Additionally, the reinforcement processing of this hybrid composite material was optimized using a Taguchi L9 (nine experimental runs) orthogonal array design with linear modeling through the Design of Experiment (DoE) principles. The fibers were alkali-treated with sodium hydroxide (NaOH), and the composites were manufactured through the hand lay-up process at ambient temperature and characterized comprehensively using ASTM standard methods. The experimental results of the bamboo–glass fiber composite materials presented a significantly high tensile strength of 232.1 MPa and an optimum flexural strength of 536.33 MPa. Based on the overall Taguchi and linear modeling analysis, the NaOH treatment, fiber content, and epoxy resin concentration were optimized. These findings reveal that the ideal combination consists of 20% fiber content, 8% NaOH treatment, and 65% epoxy resin concentration. The statistical method Analysis of Variance (ANOVA) was employed to confirm the significance of these factors. The integration of the amount (%) of bamboo fiber used played a pivotal role in influencing the mechanical properties of this hybrid composite. Overall, this study demonstrates that the reinforcement of natural fiber with polymeric material composites on epoxy enhanced the composite characteristics and quality. Therefore, this bamboo–glass–epoxy-based composite can be recommended for lightweight structural applications, especially in the automotive sector, in the future.

Keywords: bamboo fiber; process optimization; epoxy resin; mechanical properties; ANOVA; hybrid composite

1. Introduction

Natural fibers (NFs) are indeed a plentiful and easily available component in nature. They are biocompatible, have a low cost for each unit volume, are robust, and have some rigidity to them. NF composites outperform chemically manufactured fiber-reinforced composite (FRC) materials concerning both cost and ecological impact. Plant fibers are an important component in polymer-based composite materials. This appears to be due to their being compostable, inexpensive, and renewable [1]. When compared to glass fibers, natural fibers have a low density, small cost, low energy consumption, are dispersed globally, are carbon-neutral, have no abrasion when machining, represent no health concern when inhaled, and can be easily disposed of because they are biodegradable [2]. Natural fiber absorbs a lot of moisture and seems to have poor adherence between both fibers that have not been treated and the polymer matrix, which could promote deboning/disbanding over time [3]. Natural fibers are fibers manufactured from natural resources, including plants and perhaps other living creatures, and they might be either fibrous or non-fibrous (particulates) in nature. NFs as reinforcement within composites have piqued the curiosity of scientists due to their numerous advantages [4]. Natural fibers are well positioned to replace synthetic fibers in a range of conditions and applications because of their features, characteristics, and benefits such as cheap rate, light weight, and greater biodegradability. Plant fibers play an essential role in polymer-based composite materials. The reason for this is their inexpensiveness, biodegradability, and ability to regenerate [5]. Depending on the application, many varieties of fiber composites (natural–synthetic composites, natural, and synthetic) can be reinforced [6]. The expression "natural fibers" can apply to an extremely broad range of fibers. The entire fibers are sourced and derived from the natural material source. They could either be animal fibers (for example, animal hair/chicken feathers) or the fibers of plants (seed, leaf, etc.). The fibers of natural composites have additional conservational/ecological benefits, for instance, reduced pollutant and greenhouse gas emissions as well as component decomposability/biodegradability and chemical stability. Natural and synthetic fibers have found significant applications within a range of areas, including the building, car, biomedical, and marine and aircraft industries [7]. Natural fibers have extremely complicated structures. Cellulose, hemicelluloses, pectin, and lignin make up their three-dimensional structure. They are composed in hydroxyl ions and can be found throughout fiber walls. NFs, for example, can be thought of as microscopic FRCs by themselves. Fibers of bamboo are the final significant plant material that has not been completely consumed and utilized. They are mostly made up of cellulose fibrils wrapped in a lignin matrix. Non-essential components such as low-weight extractive and inorganic ashes are also included. Cellulose is the most abundant naturally occurring polymer on the planet and is the fundamental structural component of plant fibers. Polysaccharide polymers with shorter polymer chains than cellulose are known as hemicelluloses. A trustworthy agent may be responsible for the stiffness of the walls of plant cells. Fibers of bamboo have a higher lignin concentration compared to other natural fibers, thus making bamboo fibers brittle [8]. Fibers of bamboo are a plentiful natural resource with mechanical qualities similar to glass fibers, which are often utilized within plastic FRCs. Fibers of bamboo are noticeable among natural fibers because of the plant's rapid growth and high output [9]. The behavior of hybrid composites is the weighted sum of the individual components, in which the inherent advantages and limitations are better balanced when employing a hybrid composite that has two or more types of fiber. Artificial fibers, natural fibers, and a combination of artificial and natural fibers could all be utilized to make hybrid composites. As compared to fiber-reinforced composites, hybrid composites could enable the retention of a greater level of performance with a better combination of properties [10]. The flexural characteristics occurring in hybrid composites utilizing alkali treatment for fibers of bamboo were improved. Surface modifications in fibers of bamboo would efficiently eliminate contaminants and bind fibers, resulting in varied testing results depending on the various compositions classified in different amounts. This surface modification is owing to bamboo fibers' hydrophilic character, which necessitates multiple approaches for increasing interfacial surface adhesion. The elimination of amorphous hemicellulose within alkali treatment results in the greater crystallinity of bamboo fibers [11,12]. Bamboo fibers are extracted or removed from bamboo stems and chopped into three diameters, 15 mm, 10 mm, and 5 mm, without first being treated with chemicals, utilizing three distinct concentrations of sodium hydroxide (NaOH) (4%, 6%, and 8%). Following Analysis of Variance (ANOVA), it was observed that perhaps the percentage of fiber that has the largest effect on tensile and flexural characteristics is much more vital, following the overall fiber length and weight percentage of sodium hydroxide (NaOH) concentration. Regarding the primary influence, it was revealed that composites containing 10 mm fiber lengths, 6% NaOH treatment, and 10% fiber content had improved flexural and tensile performance, optimizing alkaline treatment factors that affected the mechanical characteristics and behavior of bamboo epoxy FRCs [13]. These factors include the amount of NaOH, the time spent soaking, and the time spent drying. The optimal condition was determined to be 5.81% NaOH following 3.99 h of soaking and 72 h of drying [14,15]. Experimenting with Taguchi's design approaches provides a simple, effective, and methodical strategy for maximizing experimental settings and determining their impact on process parameters. This approach employs a one-of-a-kind orthogonal array design to produce lower variation for such optimal production experimentation parameter settings. In this work, we study the effect of alkaline treatment factors on the mechanical properties and behavior of bamboo epoxy fiber-reinforced composites. We focus on the optimization of these properties of composites. These variables include the amount of NaOH used, the amount of bamboo fiber, and the amount of curing agent, which is epoxy resin [16]. The extraction of fiber from the bamboo plant is the primary focus of this work because fiber strength influences the newly developed composite to a higher extent, including the method of fiber length preparation. After extraction, an alkali treatment is performed to remove the cellulose and lignin, which affects the fiber's strength. In this work samples with amounts of bamboo fiber and glass fiber in varying percentages with epoxy are fabricated [16].

2. Materials and Methods

2.1. Matrix Material

Epoxy resin, produced by Abay Esdee Paints Jelaram Esdee Manufacturing Ltd., (Addis Ababa, Ethiopia) was used in this study. In terms of flexural and tensile strength, fatigue resistance, bond strength, and adhesive characteristics, this type of resin performs better than other resin categories. Catalysts are added to epoxy resin during the curing process, which causes chemical changes while altering the resin's composition. The epoxy resin and monomer component are chemically transformed into solid form by its catalyst.

2.2. Bamboo Fiber

A chemical treatment method was used to remove the lipid and protein components from the natural fiber obtained from the bamboo plant. The bamboo was mechanically collected from a local plant in a region of Ethiopia. After treatment, it was cut to a fiber length of 10 mm, which was the desired length. Electronic fiber-glass, a synthetic fiber, was procured from Addis Ababa, Ethiopia, from a local store, because of its affordability, strength, and availability. Bamboo fiber segments were harvested and softened in a water and sodium hydroxide mixture for five days. The amount of sodium hydroxide used to treat the natural fiber, which is bamboo fiber, was determined. A rubber mallet was used to split and release bamboo strands by applying slow and progressive pressure. The resulting fiber bundle was combed using a wire comb, and individual fibers were separated through repeated beating and combing.

2.3. Fiber and Matrix Volume Content of the Composite

In the design, fabrication, and analysis of composite materials, the determination of ingredient percentages, such as fiber and matrix (resin) fraction, in the laminate is an important task. These components are microstructural elements of the composite laminate in which the composite's strength and properties are determined and limited by these values.

Fiber and matrix weight fraction (WF, WM):

$$\text{Fiber weight fraction} = \frac{\text{weight of fiber}}{\text{Total weight}},\ W_f = \frac{W_f}{W_f + W_m} \tag{1}$$

$$\text{Matrix Weight Fraction} = \frac{\text{Weight of matrics}}{\text{Total Weight}},\ W_m = \frac{W_m}{W_f + W_m} \tag{2}$$

$$W_f + W_m = W_c \tag{3}$$

Fiber and matrix volume fraction (VF, VM):

The volume of the fibers, matrix, and composite is given by:

$$\mathrm{V_f} = \frac{\mathrm{W_f}}{\mathrm{\rho_f}}; \mathrm{V_m} = \frac{\mathrm{W_M}}{\mathrm{\rho_m}},\ \mathrm{V_C} = \mathrm{V_f} + \mathrm{V_m} \tag{4}$$

$$\text{Fiber Volume fraction} = \frac{\text{Volume of fiber}}{\text{Total volume}}\ \mathrm{V_f} = \frac{\mathrm{V_f}}{\mathrm{V_m} + \mathrm{V_f}} = \frac{\mathrm{V_f}}{\mathrm{V_c}}, \tag{5}$$

$$\text{Matrix Volume Fraction} = \frac{\text{Volume of matrix}}{\text{Total Volume}},\ \mathrm{V_m} = \frac{\mathrm{V_m}}{\mathrm{V_m} + \mathrm{V_f}} = \frac{\mathrm{V_m}}{\mathrm{V_c}} \tag{6}$$

V_m + V_F = 1. Let ρ_f and $]\rho_m$ represent the density of the fiber and matrix, respectively.

$$\mathrm{V_{f=\frac{W_F*\rho_m}{W_f*\rho_m+W_m*\rho_f}}} \tag{7}$$

Similarly:

$$V_{m=\frac{W_m*\rho_f}{W_f*\rho_m+W_m*\rho_f}} \tag{8}$$

where $\mathrm{V_m}, \mathrm{V_f}$ = volume of matrix and fiber, $\mathrm{W_F}, \mathrm{W_m}$ = weight of fiber and matrix, $\mathrm{\rho_{f,\rho_m}}$ = density of fiber and density of matrix, $\mathrm{W_F}, \mathrm{W_m}$ = matrix weight fraction and fiber weight fraction, and $\mathrm{W_c}, \mathrm{V_c}$ = weight of composite specimen and volume of composite specimen.

2.4. Mechanisms of Composite Processing and Production

Hand layup was used to construct the laminate hybrid composites. A discharge gel (waxed) was initially placed onto the mold to restrict fibers from sticking to it. The thermosetting polymer was heavily mixed with the chipped structural reinforcement in the liquid state. A glass fiber piece with a matted structure and a specified dimension determined by the sample size was already in a mechanically stirred mold when the polymer solution was applied. A ratio of resin to hardener of 3:1 was used while mixing. This process was repeated for each layer of the polymer matrix until all required layers had been added. Spraying discharge gel over the interior surface and topmost mold panel causes it to stick to that convolution layer. The percentages of each fiber concentration and epoxy resin were calculated separately without taking into account the three components' anticipated percentage sum of 100%. The amounts of bamboo fiber, sodium hydroxide, and epoxy were 10–20%, 4–8%, and 60–70%, respectively, as specified in the introduction section.

2.5. Optimization Using Taguchi Method

An L9 orthogonal configuration was used to carry out nine-sample fabrication for experimentation. The wt.% of bamboo ranged between 10% and 20%, the NaOH pretreatment ranged from 4% to 8%, and the epoxy wt.% ranged between 60% and 70%. For all 9 experimental trials, the fiber-glass content was adjusted to 20%. All the experiments used 3 levels of fiber-glass. The signal-to-noise ratio was calculated as the proportion of the mean/average signal value to the competence noise level for various characteristics, as shown in the equations below.

$$\frac{S}{N} = -10\log_{10} \text{sum}\left(\frac{1}{Y^2}/n\right) \text{ Higher is better} \quad (9)$$

$$\frac{S}{N} = 10\log_{10}\left(\frac{y^2}{S^2}\right) \text{ Normal is the best} \quad (10)$$

$$\frac{S}{N} = -10\log_{10} \text{sum}\left(Y^2/n\right) \text{ Smaller is better} \quad (11)$$

Here, Y represents the necessary data (bamboo wt.%, NaOH treatment wt.%, and epoxy wt.%) and n represents the number of repetitions. Table 1 displays the process/contribution variables and their levels employed in the fabrication of bamboo–glass fiber hybrid composites.

Table 1. Control variables and levels of bamboo and glass fiber in the composite.

Governing Variables	Designation	Level 1	Level 2	Level 3
1. Fiber of bamboo, wt.%	A	10	15	20
2. Treatment with NaOH, wt.%	B	4	6	8
3. Epoxy within hardener, wt.%	C	70	65	60

3. Experimental Design

The orthogonal array selection was based on the overall degree of freedom (DoF) of the process variables according to the Taguchi Design of Experiment (DOE) principle. The degree of freedom (DoF) of the orthogonal array must be larger than or equal to the planned number of control variables [17]. Throughout this investigation, the L9 orthogonal array (OA) considers three factors: a fiber's content, B's NaOH content, and C's epoxy content, in the three phases of analysis. To reduce variance and enhance process variables, the Taguchi methods use orthogonal arrays. As a competency capability criterion, the signal-to-noise (S/N) ratio is used to evaluate process robustness and deviation from target values [18]. Any logarithmic variable's S/N ratio can be calculated by calculating the ratio of signal to noise. To lessen noise and the effects of uncontrollable factors, higher S/N ratio values are preferred [19]. High S/N ratios are an indication of a high-quality product. Table 2 displays the list of experimental runs.

Table 2. L9 orthogonal array (OA) and levels of control factors.

Runs	Bamboo Fiber (% wt.)	NaOH Treatment (% wt.)	Epoxy Resin (% wt.)
1	10	4	70
2	15	4	65
3	20	4	60
4	10	6	65
5	15	6	60
6	20	6	70
7	10	8	60
8	15	8	70
9	20	8	65

3.1. Analysis of Variance

ANOVA is a two-way variance analysis that investigates trial design characteristics that have a strong influence on reactions to various stimulations. A table of Analysis of Variance (ANOVA) is also frequently employed to investigate the interconnections between factors and their effects on the dependent variables. A high F-value specifies that a process variable has a considerable influence on the attribute. If the value of $p < 0.05$ is at a 95% level of confidence, the variables and relationships are deemed significant. The adjusted correlation coefficient, R^2adj, is used for assessing fit occurring in the model. It computes the wt.% of variance that could be analyzed solely using the exogenous variables and interconnections that have the greatest influence on the response variables. Furthermore, to infer that the constructed models match the completed tests effectively, the values of R^2 and R^2adj should be significant and near to each other [20].

3.2. Optimization for Multiple Responses

Utilizing grey relational analysis (GRA), Taguchi's method is acceptable in the direction of determining the maximal setting of process variables to achieve a particular reaction. Grey relational analysis could be exploited to establish uniformity between apparently uneven predetermined data and facts. Multiple-response optimization utilizing GRA recommended many approaches, each with distinct advantages. All mechanical characteristics (tensile, flexural, compressive, and impact measurements) were converted into S/N ratios in this investigation. GRA multi-response optimization consists mostly of three phases. The response is translated into a normalized form in the first step.

3.3. Normalizing Sequence

The GRA optimization process differs from the Taguchi approach in its methodology. The purpose of this normalization is to decrease variances in the range of responses. The following formula was employed to standardize the two quality criteria, with 'larger-the-better' attributes, as shown in Equation (12).

$$X_{ij} = \frac{Y_{i(j)} - \min Y_{ij}}{\max Y_{i(j)} - \min Y_{i(j)}} \quad (12)$$

Sequence of deviation determination:

In the above equation, $\Delta_i(j)$ represents variance order data and X_0(j) is the outcome of the experimentation for the 0th investigation employing the jth reply. (j) signifies the investigational outcome of the ith experimentation by the jth reply, as shown in Equation (13) below.

$$\Delta_i(j) = |X_0(j) - X_i^*(j)| \quad (13)$$

Grey relationship coefficient derivation:

In the above equation, $\Delta_i(j)$ is the absolute value of the difference between X_0(j) and $X_i^*(j)$, and $\Delta \boldsymbol{max}$ and $\Delta \boldsymbol{min}$ are the global maximum and global minimum values in different data series. Generally, the distinguishing coefficient (n) = 0.5 is taken. After the responses were normalized, the grey relational coefficient (GRC) was calculated using the following equation.

$$\xi_i(j) = \frac{\Delta \min + \xi \Delta \max}{\Delta i(j) + \xi \Delta \max} \quad (14)$$

ξ is considered to be 0.5.

Grey relation grade (GRG) determination:

The mean of the GRC of each quality characteristic was used to estimate the grey relational grade (GRG), as depicted in the following Equation (15).

$$\gamma_i = \frac{1}{N} \sum_{j=1}^{n} \xi_i(j) \quad (15)$$

4. Analysis of Flexural and Tensile Properties

4.1. Flexural Properties

The flexural strength developed in the composite maximized the tensile stress, which the composite can tolerate when bending before fracturing. All composite samples were subjected to the three-point bend test using a Universal Testing Machine (UTM). The specimens were created in compliance with the ASTM standards (D790-2010) [16]. Each specimen was 60 mm × 10 mm × 3.5 mm. The span length was kept at 40 mm and the crosshead speed was kept at 10 mm/min. The experiment regarding flexural strength was conducted 3 times on each variety of composite, with the mean rate recorded. The flexural strength developed in the composite sample was calculated through the formula shown in the equation below.

$$\text{Flexural Strength} = 3PL/2bh^2 \quad (16)$$

where P is the highest force exerted on the test sample (N), L is the span support (mm), b is the specimen's breadth (mm), and h is the specimen's thicknesses (mm).

4.2. Tensile Properties

Tensile strength examinations were implemented to determine tension pressures. The tensile properties are used to calculate elastic limit, modulus of elasticity, area reduction, elongation, and other properties [21–24]. The prepared sample's dimensions were 200 mm × 13 mm × 3.5 mm with a dog bone form, and uniaxial stress was applied/loaded on both edges of the ends. The Universal Testing Machine was used to perform the ASTM standard investigation technique aimed at determining the tensile characteristics occurring in a Fiber Refractory System (FRS) according to ASTM D3039, as shown in Figure 1.

Figure 1. Tensile examination samples.

These examinations of the prepared specimens were carried out using a UTM machine with a HUT-1000 series of microchip controlled Electro-hydraulic servo. A crosshead speed of 10 mm/min was maintained to determine the tensile strength of the composite specimen. The examination was repeated 3 times for all specimen composite types and the mean rate was given to determine the tensile strength.

5. Results and Discussion

5.1. Mechanical Property Analysis

The mechanical properties of the hybrid composites were examined in the form of tensile and flexural strength tests. The grey relational analysis and Taguchi methods were also utilized to promote the maximization/optimization of mechanical behavior. The formulation of the experimental method selected the optimal experimentation for improving mechanical qualities.

5.2. Flexural and Tensile Properties

In this study, bamboo fiber, epoxy resin, and NaOH treatment were used as control variables to examine how mechanical qualities vary. It is clear that 20% synthetic fiber, or glass fiber in each sample, and that the volume fraction analysis in section two, were used to arrive at this figure. According to the samples' thickness, three layers of glass fiber were used in the sample production in the top, middle, and bottom sections. The most superior characteristic was chosen to study the effects of variables on the multiple replies. The S/N ratios are used to summarize the experimental results in Table 3. The variation in tensile strength versus epoxy with varying amounts of NaOH% is shown in Figure 2.

Table 3. Taguchi method L9 OA findings with the S/N ratio.

Run	Fiber wt.%	NaOH wt.%	Epoxy wt.%	Flexural Strength (MPa)	S/N Ratio	Av. Tensile Strength (MPa)	S/N Ratio
1	10	4	70	146.94	43.34	89.6	39.05
2	15	4	65	242.45	47.69	166.7	44.44
3	20	4	60	286.53	49.14	210.3	46.46
4	10	6	65	117.55	41.4	149.4	43.49
5	15	6	60	205.7	46.26	135.2	42.62
6	20	6	70	330.61	50.39	194.1	45.76
7	10	8	60	271.84	48.68	187.0	45.44
8	15	8	70	127.35	42.10	128.4	42.17
9	20	8	65	536.33	54.59	232.1	47.31

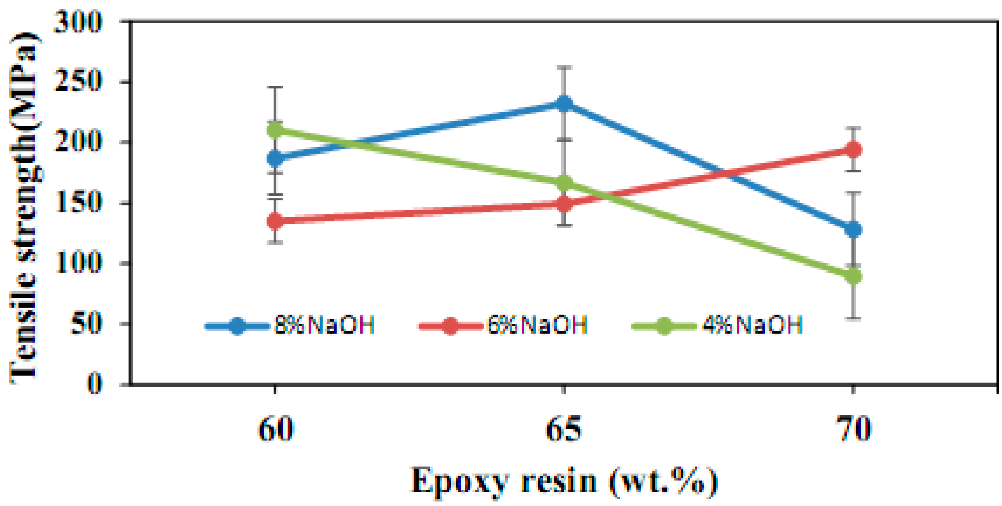

Figure 2. Tensile strength versus epoxy with varying amounts of NaOH%.

Natural-fiber-reinforced epoxy composites were explored based on prior research, both untreated and alkali-treated. Alkali-treated fiber composites are stronger than chemically changed fiber composites in terms of tensile strength. Tensile strength increased as fiber content increased, reaching its highest at 20% of fiber [24]. The tensile strength at various fiber concentrations is shown in Figure 3.

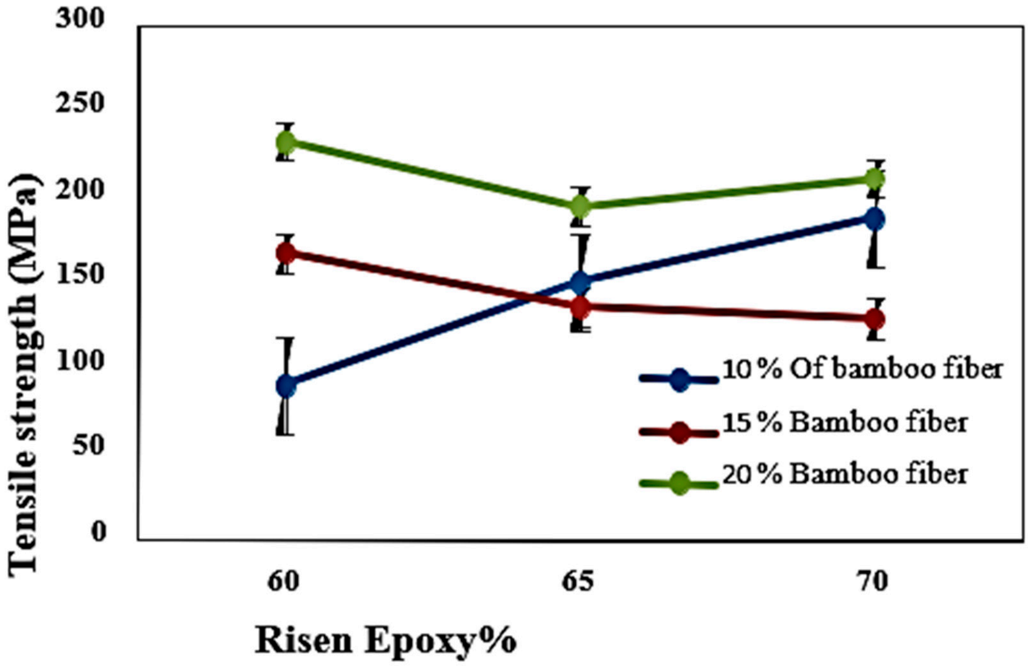

Figure 3. Tensile strength versus epoxy % with various fiber concentrations.

Figures 4 and 5 show the impact of fiber content variation and alkali treatment on the flexural strength of bamboo fiber wt.% at different percentages of NaOH and epoxy. When the reinforcing bamboo fiber was raised from 10% to 20%, the composite's tensile strength increased from 89.6 MPa to 210.3 MPa. Flexural strength was observed to be enhanced when alkali-treated bamboo fibers were employed in hybrid composites with a NaOH solute concentration of 4, 6, and 8% in weight. When the mechanical characteristics of the samples were specifically analyzed, the sample with bamboo fiber that had been treated with 8% and had an amount of bamboo fiber of 15%, while maintaining an amount of glass fiber of three layers, had lower flexural strength due to the high amount of epoxy resin that served as the binding agent. The morphological analysis can provide additional evidence of this.

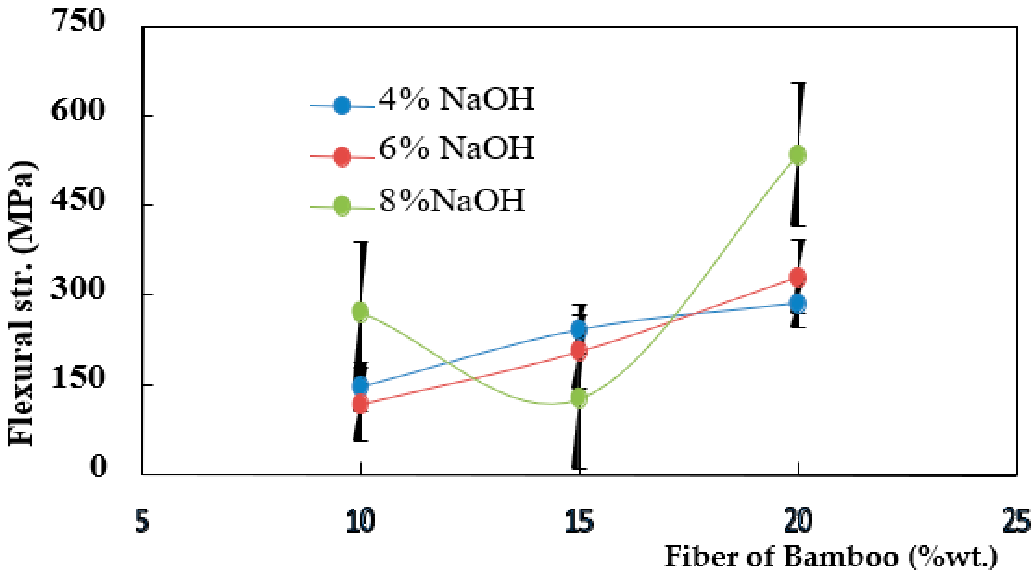

Figure 4. Flexural strength versus fiber of bamboo wt.%.

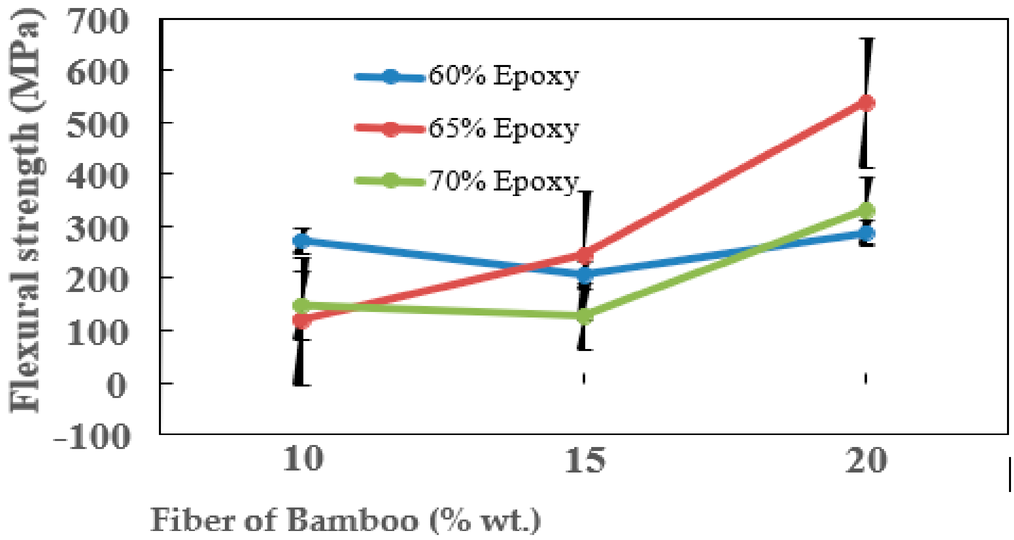

Figure 5. Flexural strength versus fiber of bamboo.

As the amount of bamboo fiber in the epoxy resin increased, the impact on the flexural properties of the hybrid composites increased to a greater extent. When alkali-treated bamboo fibers were included in the hybrid composites, it was discovered that these qualities were improved. These data could be explained by the alkali treatment's removal of amorphous hemicellulose, which increased the crystallinity of the bamboo fibers.

6. Discussion of Tensile and Flexural Strengths

6.1. Tensile Strength

The delta score values in the response table with means were used to identify the major control variables, according to Table 4. The delta score values were computed through subtraction of the greatest and lowest average scores of each component. The differential value was then used to give ranks. The highest delta score value was allocated the primary rank/score and indicates the most important variable influencing tensile toughness/strength. According to Table 4, the most significant variable was fiber of bamboo (wt.%) with a delta score of 3.85, followed by epoxy resin with a delta score of 2.75 and NaOH (wt.%) with just a score of 1.66. As shown in Table 4, changes in the quantity of bamboo fiber significantly affected tensile strength. In natural FRCs, their tensile strength often increases with only a slight increase in fiber weight percentage. "1" in Table 4 shows that these values stand as rank 1 and are critical for tensile strength.

Table 4. Analysis of tensile strength S/N ratio response.

Level	NaOH%	Fiber of Bamboo%	Epoxy Resin%
1	43.31	42.66	44.84
2	43.96	43.08	**45.08** [1]
3	**44.97** [1]	**46.51** [1]	42.33
Delta	1.66	3.85	2.75
Rank	3	1	2

[1]: in the Table 4 shows that these values stands as rank 1 and are critical for tensile strength.

One conclusion is that fibers can endure tensile characteristic elongations under high pressure if a strong link is formed between them and this link is formed as a result of the configuration of the fibers. Figure 6 shows significantly increasing S/N tensile strength pattern ratios from 10% to 20%. The relationship between epoxy resin concentration and the S/N ratio shows a growing trend from 60% to 65%. When the epoxy fraction reaches 70%, the value sharply declines.

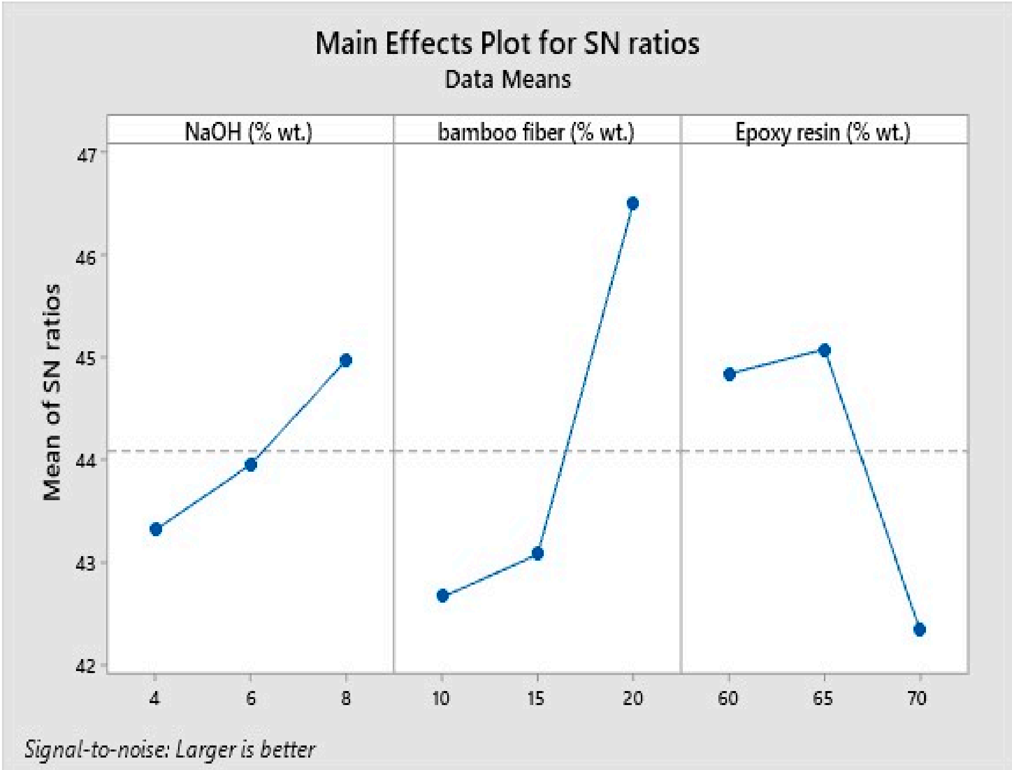

Figure 6. The main effect of tensile strength in terms of S/N ratios.

ANOVA (which can be seen in Table 5) was utilized to compute the percentage involvement of every element's influence mostly on the tensile strength of the composite. It could determine that bamboo fiber does have the greatest impact on the tensile durability of the composite, with a contribution of 60.17%, followed by epoxy resin% wt., with 23.05%, and finally, NaOH% treatment with 7.91%. Factors with a p-value/score < 0.05 are considered important at a 95% level of assurance/confidence. According to Table 5, the null hypothesis cannot be accepted because the p-value/score for bamboo fiber is less than 0.05. At a 95% level of assurance/confidence, the variable does have a considerable influence on tensile strength.

Table 5. Variance analysis of tensile strength.

Source	DF	Adj SS	Adj MS	F-VALUE	p-VALUE	PC
NaOH%	2	1269	634.7	0.89	0.528	7.91%
Bamboo fiber (% wt.)	2	9650	4824.8	6.78	0.028	60.17%
Epoxy resin (% wt.)	2	3696	1848.1	2.60	0.278	23.05%
ERROR	2	16,038	711.1	0.00	0.00	4.43%
TOTAL	8	54,077		0.00	0.00	100.0

Model summary: S = 26.67; R^2 = 91.13; R^2(adj) = 64.53.

6.2. Flexural Strength

According to Table 6, which shows the S/N ratios, the most important element for flexural strength is fiber content, followed by epoxy resin percentage and NaOH percentage. The results of the analysis lead to the conclusion that fiber content, epoxy resin weight percentage, and NaOH weight percentage have a substantial impact on flexural strength maximization. An ANOVA was performed to validate the most important factor. Figure 7 shows the details of the flexural test samples.

Table 6. Data of flexural strength S/N ratio responses.

Level	NaOH (wt.%) (B)	Fiber of Bamboo (wt.%) (A)	Epoxy Resin (wt.%) (C)
1	46.73	44.48	**48.03** [1]
2	46.02	45.35	47.90
3	**48.46** [1]	**51.37** [1]	45.28
Delta	2.44	6.89	2.76
Rank	3	1	2

[1]: in the Table 6 shows that these values stands as rank 1.

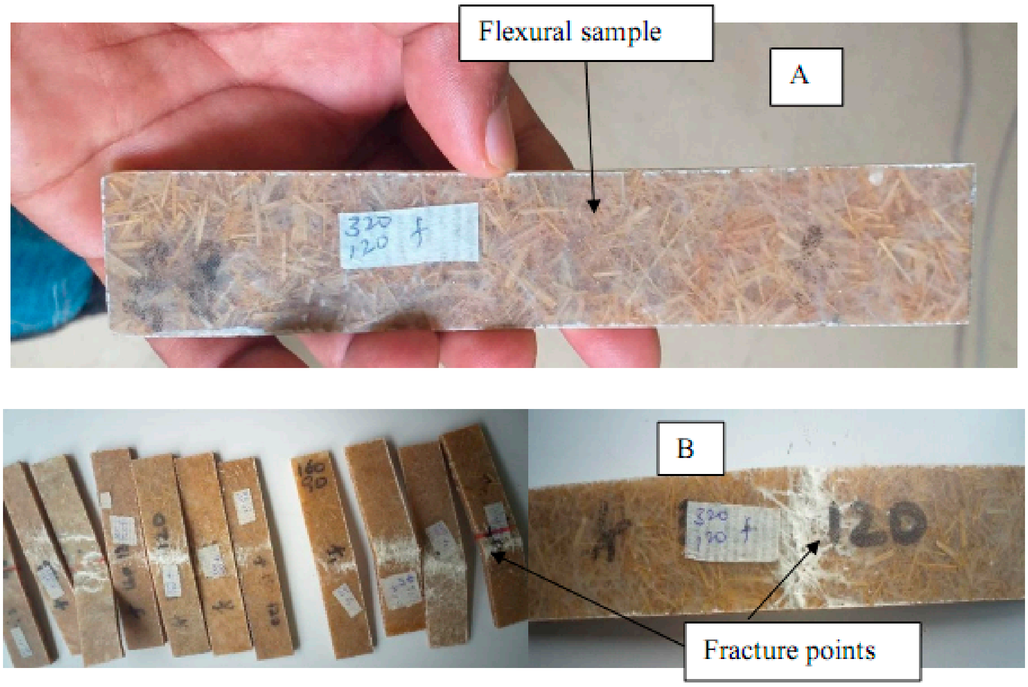

Figure 7. Flexural test samples (**A**) before bending and (**B**) after bending.

Figure 8 graphically illustrates the process factors' influence on flexural strength. The graphs show how the governing variable settings changed with the change in S/N ratio. For the factor with the least influence, the graph's lines are practically level, and for the factor with the greatest effect, they have the largest slope. Fiber content is the most crucial factor, with epoxy content and NaOH% having just a small impact. According to our findings, the best bamboo composites are those made with fibers treated with 8% NaOH; nevertheless, flexural strength is reduced when the NaOH content is increased above 8% or decreased below 6%. When bamboo fibers are used as filler at a rate of 10%, 15%, and ultimately, 20%, flexural strength increases. Flexural strength in a fiber decreases as the proportion of epoxy resin rises from 60% to 70%. The fiber's adhesion to the matrix is weak as a result of an increase in the amount. The figure below illustrates the combination of factors (B3), (A3), and (C1), which offer the highest level of flexural strength.

Based on the Table 7 output, the influencing parameters include the content of fiber (p = 59.32%), epoxy resin (p = 25.26%), and NaOH% (p = 12.34%). The R^2 and R^2 adj values are greater and equivalent to one another. This shows the model's quality of fit. The error of (p = 3.08%) signifies that this model is well-fitting.

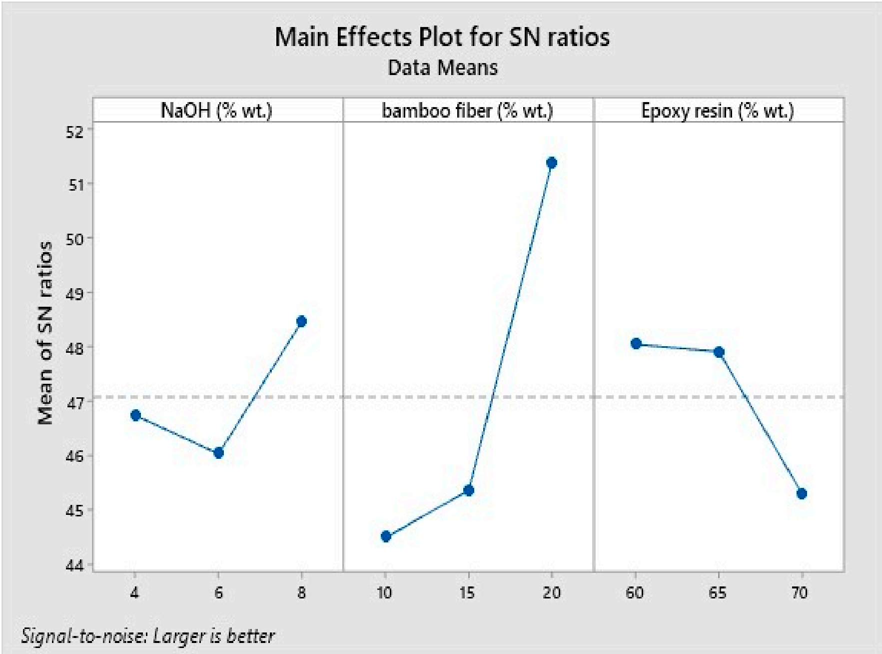

Figure 8. A main/principal effects graph with flexural strength S/N ratio.

Table 7. Variance analysis of flexural strength.

Source	DF	Adj SS	Adj MS	F-Value	*p*-Value	PC
NaOH%	2	16,716	8358	4.00	0.200	12.34%
Fiber of bamboo%	2	80,371	40,186	19.23	0.049	59.32%
Epoxy resin%	2	34,227	17,113	8.19	0.109	25.26%
ERROR	2	4180	2090	0.00	0.00	3.08%
TOTAL	8	135,494		0.00	0.00	100.0

Model summary: S = 47.72%; R-sq = 47.72% 93.17%; R-sq(adj) = 87.66%.

6.3. GRG Optimization Depended on Multi-Response

The optimization of multi-responses utilizing GRA is a recommended method for determining performance characteristics. Table 8 below shows the normalizing and deviating sequencing of GRG for tensile and flexural strength. The combination of ideal settings that optimize the overall responses may be determined using the GRG responses provided in Table 8. The maximal grey relationship coefficients are shown in Table 9, i.e., the NaOH and bamboo fiber at the third level and epoxy resin at the second level. As a result, the most recommended parameter settings for flexural and tensile properties within the composite are fiber of bamboo at 20%, treatment with alkali at 8%, and epoxy resin at 65%.

Table 8. Normalizing values and deviation sequence of GRG.

	Normalizing Values		Deviation Sequence	
S. No	Tensile Strength (MPa)	Flexural Strength (MPa)	Tensile Strength (MPa)	Flexural Strength (MPa)
1	0.0000	0.0702	1.0000	0.9298
2	0.5411	0.2982	0.4589	0.7018
3	0.8470	0.4035	0.1530	0.5965
4	0.4196	0.0000	0.5804	1.0000
5	0.3200	0.2105	0.6800	0.7895

Table 8. *Cont.*

S. No	Normalizing Values		Deviation Sequence	
	Tensile Strength (MPa)	Flexural Strength (MPa)	Tensile Strength (MPa)	Flexural Strength (MPa)
6	0.7333	0.5088	0.2667	0.4912
7	0.6835	0.3684	0.3165	0.6316
8	0.2723	0.0234	0.7277	0.9766
9	1.0000	1.0000	0.0000	0.0000

Table 9. Grey relational coefficient of GRG.

Grey Relational Coefficient Analysis		GRG	Rank
Tensile Strength (MPa)	Flexural Strength (MPa)		
0.3333	0.3497	0.11384	9
0.5214	0.4161	0.1562	5
0.7657	0.4560	0.2036	2
0.4628	0.3333	0.1327	7
0.4237	0.3877	0.1352	6
0.6522	0.5044	0.1927	3
0.6124	0.4419	0.1757	4
0.4073	0.3386	0.1243	8
1.0000	1.0000	0.3333	1

Fiber of bamboo does have the greatest influence on GRG (59.23%), followed by NaOH wt.% (17.01%) and epoxy resin (16.93%). Because the p-value of bamboo fiber, factor (A), is <0.05, this variable has a considerable impact on the composite's tensile and flexural properties. The higher R value/score indicates the model's quality of fit. The main effects plot for the means of GRG is shown in Figure 9. Table 10 depicts the GRG response data as means. Table 11 depicts the GRG variance analysis of all factors.

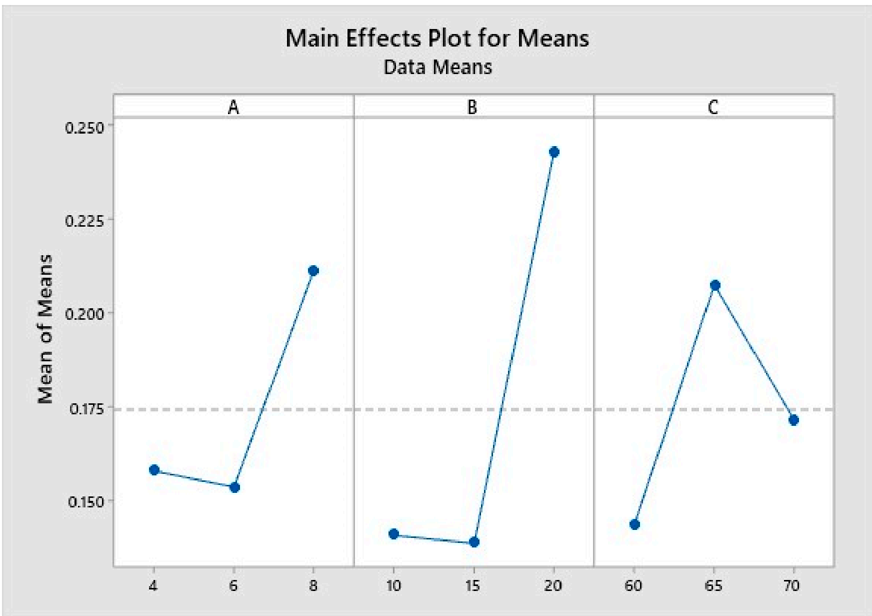

Figure 9. The main effects plot for means of GRG: (**A**) NaoH%, (**B**) bamboo fiber%, (**C**) epoxy resin%.

Table 10. GRG response analysis data as means.

Level	NaOH(A)	Fiber of Bamboo(B)	Epoxy Resin(C)
1	0.1579	0.1407	0.1436
2	0.1536	0.1386	**0.2074**
3	**0.2111**	**0.2432**	0.1715
Delta	0.0576	0.1046	0.0638
Rank	3	1	2

Table 11. GRG variance analysis.

Source	DF	Adj SS	Adj MS	F-Value	*p*-Value	PC
A (NaoH%)	2	0.006163	0.003081	2.49	0.286	17.01
B (bamboo fiber%)	2	0.021459	0.010729	8.67	0.013	59.23
C (epoxy resin%)	2	0.006135	0.003067	2.48	0.287	16.93
ERROR	2	0.002475	0.001237	0.00	0.00	6.83
TOTAL	8	0.036231		0.00	0.00	100.0

Model summary: S = 0.0351751; R-sq = 93.17%; R-sq(adj) = 72.68%.

6.4. X-ray Tests

A quick, rational, systematic procedure known as X-ray powder diffraction (XRD) provides factual information on unit cell size as well as crystalline phase determination. Before determining the bulk average composition, the main material/components under examination were coarsely pulverized and homogenized. The orientations and packing of bamboo fiber-glass within the epoxy resin, as well as the optimal patterns of armored fiber-glass, were investigated using XRD analysis. A Bragg peak with an angle of 2θ = 18.42 was revealed via the XRD of a chosen composite, including 20% weight bamboo, glass fiber and 4% epoxy resin, proving the presence of bamboo crystalline fiber in the composite. The presence of crystalline bamboo fiber inside the composite was confirmed by Figures 10–12, which demonstrate that for XRD, composites with both bamboo and fiber-glass amounting to 20% and an epoxy mass of 6% disclosed a Bragg peak with an angle of 2θ = 17.30. Figure 10 shows an XRD graph of the composite containing 20% fiber of bamboo, 4% NaOH, and 60% epoxy resin. Figure 11 illustrates the amorphous nature of the materials. Figure 12 shows that the XRD of the selected composite, which contained 20% bamboo, 20% glass, and 8% epoxy resin, displayed a peak at a Bragg's angle of 2θ = 18.34, verifying the presence of bamboo crystalline fiber in the composite at that location. The chosen samples' corresponding graph peak values, however, are not the same. This demonstrates that each sample's composition and crystalline arrangement are unique. Figure 13 depicts a microstructural image of bamboo fibers.

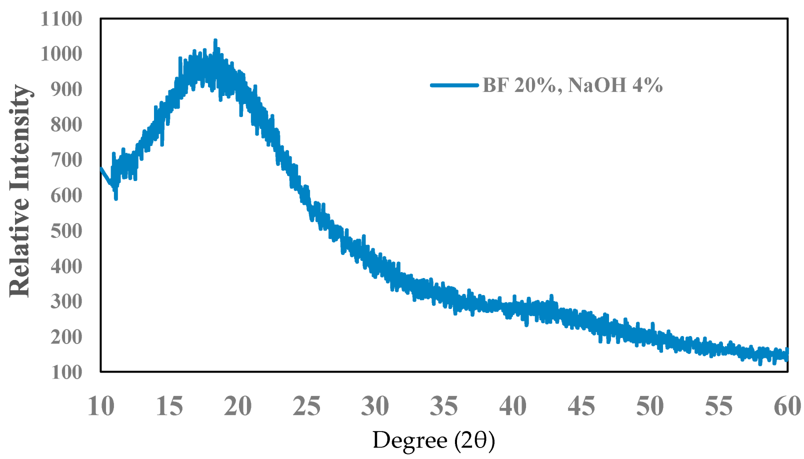

Figure 10. XRD graph of composite containing 20% fiber of bamboo, 4% NaOH, and 60% epoxy resin.

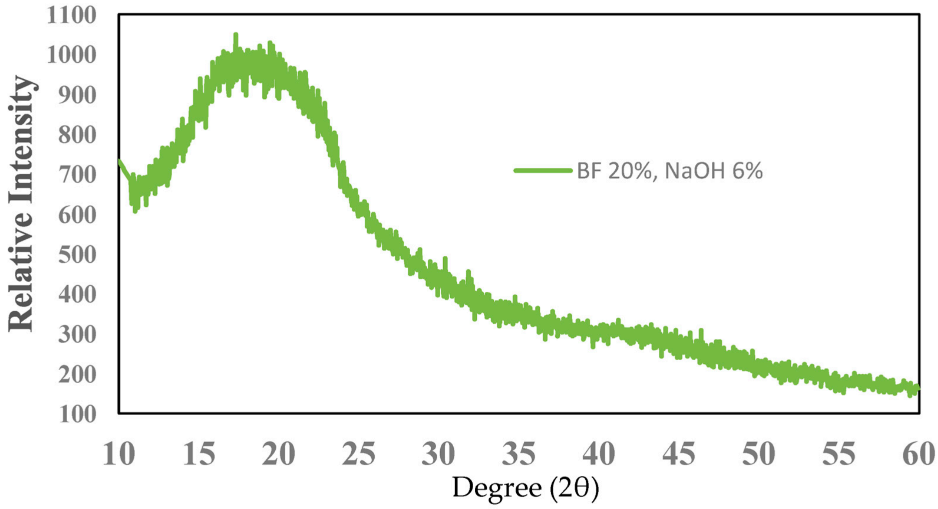

Figure 11. X-RD plot for fiber of bamboo 20%, NaOH 6%, and epoxy resin 65%.

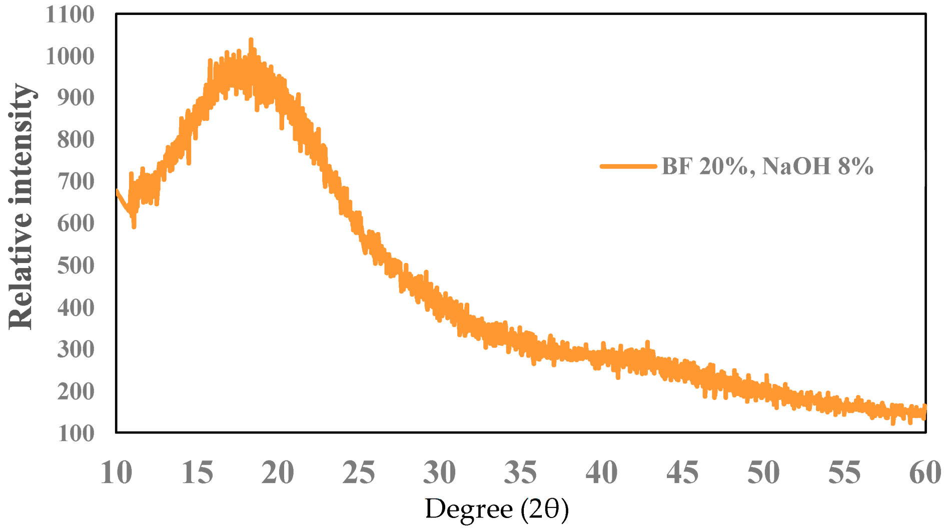

Figure 12. X-RD plot for bamboo fiber 20%, NaOH 8%, and epoxy resin 65%.

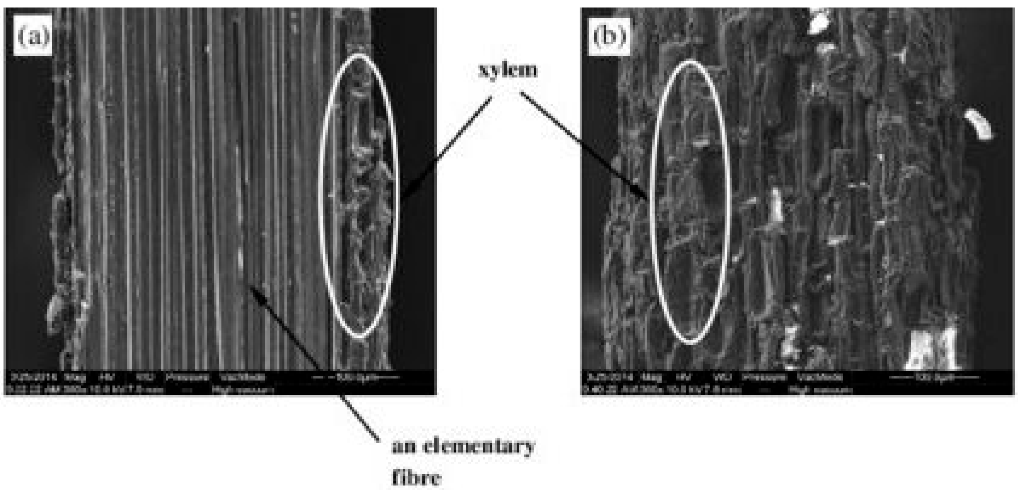

Figure 13. The microstructure of a bamboo fiber examined in this study: (**a**) longitudinal section; (**b**) surface morphology.

7. Conclusions

According to the experimental results and the analysis of the ANOVA results of the testing, the highest tensile strength of 232.1 MPa and the highest flexural strength of 536.33 MPa were found. The results show that the three main contributing factors—fiber content (20%), epoxy resin (65%), and alkali chemical treatment (8%)—were the most important ones that influenced the material properties. Therefore, it was shown that the most significant manufacturing factor affecting the overall mechanical properties of hybrid composites was the amount of bamboo fiber used. It was found that the mechanical properties of natural-fiber-reinforced polymer composites based on epoxy were successfully improved.

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