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Effects of Fiber Content on the Mechanical Properties of Betel Nut Epoxy Composites: An Experimental and Analytical Study

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ABSTRACT
This study investigates the mechanical properties of betel nut fiber-reinforced epoxy composites, focusing on the impact of different fiber contents on the composite's performance. The primary objectives are to fabricate betel nut fiber composites with varying fiber percentages (5%, 10%, 15%, and 20%) and analyze their mechanical properties through experimental and analytical methods. The study aims to assess how fiber content influences tensile strength, impact strength, hardness, Young's modulus, and density. The methodology involves chemically treating the betel nut fibers with NaOH to enhance bonding with the epoxy matrix, followed by the fabrication of composites using the hand lay-up method. Four different fiber content specimens were produced and tested. Mechanical tests such as tensile testing (using a Universal Testing Machine), impact testing (using a Pendulum Impact Tester), and hardness testing (using a Rockwell Hardness Tester) were conducted to evaluate the performance of the composites. The results show that the composite with 10% fiber content (C10) displayed the highest tensile strength of 20.38 MPa, while the composite with 20% fiber content (C20) demonstrated the highest impact strength at 16.81 J/cm². However, hardness decreased as fiber content increased, with the 5% fiber composite (C05) exhibiting the highest hardness value of 51 HBL. Both Young's modulus and density increased with higher fiber content. In conclusion, the study finds that betel nut fibers positively influence the mechanical properties of epoxy composites. The 10% fiber content composite provides an optimal balance of strength and flexibility, making it suitable for lightweight structural applications. This research highlights the potential of using natural fibers like betel nut in sustainable composite materials, offering an eco-friendly alternative to synthetic fibers.

Keywords: Betel nut fiber, Epoxy composite, Fiber content, Natural fiber-reinforced composites, Lightweight applications

1. Introduction

In recent years, there has been a growing shift towards using natural fibers in composite materials due to the demand for eco-friendly and sustainable alternatives to synthetic fibers [1], [2]. Natural fiber-reinforced composites (NFRCs), used in industries like automotive, aerospace, and construction, are valued for their biodegradability, cost-effectiveness, and good mechanical properties [3]. Among natural fibers, betel nut fiber stands out due to its availability, high cellulose content, and lightweight nature, but its potential as reinforcement in polymer composites remains underexplored [4]. A key challenge with natural fibers is their hydrophilic nature, which weakens bonding with hydrophobic polymer matrices. This issue can be addressed with chemical treatments like alkali treatment to improve fiber-matrix adhesion. Optimizing fiber content in NFRCs is crucial, as it significantly affects mechanical properties such as strength and stiffness [5], [6]. This study investigates the effect of varying betel nut fiber content (5%, 10%, 15%, and 20%) on mechanical properties like tensile strength, impact strength, hardness, Young's modulus, and density in epoxy composites.

The findings of this research are expected to contribute to the development of sustainable and eco-friendly materials that can replace conventional synthetic composites, particularly in industries seeking lightweight and biodegradable alternatives. Through this work, betel nut fiber is introduced as a viable reinforcement material for polymer composites, promoting sustainable engineering practices.

2. Methodology

Betel nut fibers are ideal for reinforcement in composites due to their high cellulose content. They can be used with epoxy resin, requiring careful selection, extraction, treatment, orientation, fabrication, and mechanical evaluation.

2.1 Fiber Collection

Fibers from betel nut tree parts like leaves, sheath, and stem are collected, with content varying based on plant age, cultivation area, and extraction process. High cellulose content and crystallinity are preferred for structural applications due to their significant impact on the mechanical characteristics of natural plant fibers [7]. Young plants have lower cellulose content, so mature plants are preferred for structural reinforcement.

2.2 Fiber Extraction

The physical and mechanical properties of natural fibers are influenced by growing methods, ambient conditions, and extraction processes, with retting being the most common method. There is classification in retting

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process [8]. In this study cold water retting process were used to extract the fibers. This method requires approximately 7 to 14 days to degrade waxes, pectin, hemicellulose and lignin [8]. In this study, retting process continued for 14 days and after extraction process, fibers were dried in sunlight to eliminate moisture content.

2.3 Chemical Treatment

Plant fibers are hydrophilic due to high cellulose content, while polymer matrices are hydrophobic because of their chemical composition, posing challenges for natural fiber reinforcement in polymer composites as these differences reduce mechanical properties [9]. Poor adhesion in the interface zone weakens load transfer, leading to reduced performance [10]. Enhancing composite properties requires improving fiber-matrix adhesion, often achieved through chemical modifications. Common methods to reduce hydrophilicity and improve compatibility include alkali treatment (NaOH), silane treatment (SiH_4), acetylation (CH_3COOH), peroxide (ROOR), permanganate ($KMnO_4$), maleated coupling agents, enzymatic, and isocyanate(-N=C=O) treatments, among others [11].

$$\text{Fiber} - \text{OH} + \text{NaOH} \longrightarrow \text{Fiber} - \text{O} - \text{Na} + H_2O + \text{surface impurities [12].}$$

The study utilized alkali (NaOH) treatment for chemical treatment of extracted fibers, which were soaked in 5% NaOH solution for 48 hours, washed with distilled water, and dried in an oven at 80°C for 24 hours [13].

2.4 Fiber Orientation

Fiber orientation in natural fiber reinforced composites influences mechanical properties. Four common orientations are unidirectional, random, perpendicular, and multidirectional. Each orientation affects composite properties differently, ensuring structural improvement and optimal performance. The mechanical properties, including flexural strength which exhibit the highest value at a 90° fiber orientation [14]. The study found that fibers performed best in flexural tests when oriented at 90° due to minimal stress generation under high flexural load [15].

2.5 Fabrication Method

Advancements in technology provide diverse strategies for composite fabrication, together with hand lay-up, injection molding, and autoclave molding. This examine employed the hand lay-up approach to fabricate a betel nut fiber reinforced polymer composite, emphasizing its versatility and fee-effectiveness for small to medium composites in comparison to other techniques like injection, compression, and autoclave molding [16], [17].

2.6 Raw Material

The materials and chemicals for fabricating the betel nut fiber reinforced composite material are as follows.

Betel Nut Leaves Fiber- Betel nuts, a Malaysian native fruit from the Areca catechu palm tree, are popular in Bangladesh for chewing alongside betel leaves and lime, and have potential applications in pharmacology and medicine [18]. The chemical composition of betel leaf fiber is characterized by more than 75% α-cellulose content, which contributes to its strength and stability, making it a strong natural fiber It also contains 12% hemicellulose, a improves flexibility and binding, and 10% lignin, with structural support decay resistance is added.

In this study, a 5% NaOH alkaline solution (pH 7–14) with distilled water was used for the chemical treatment of natural fibers. Polymer resin acts as a glue in reinforced polymer composites, transferring stress and resisting mechanical loading. Resins are classified into thermoplastic and thermoset types, with epoxy resins and thermosets commonly used for their strength and toughness, composed of phenolic glycidyl ethers, aromatic glycidyl amines, and cycloaliphatics [20]. Hardeners catalyze resin solidification to increase bonding in composites, which are generally Mixed in 10:1 resin-hardener interface.

2.7 Instruments

The mechanical testing of materials was carried out using two key instruments: the Universal Testing Machine and the Pendulum Impact Tester. The tensile test, conducted according to ASTM D638 standards, measures a material's response to tensile forces, which is crucial for applications involving pulling or stretching. The tensile stress (σ) is calculated using the equation:

$$\sigma = \frac{F}{A} \tag{1}$$

where F is the applied tensile load and A is the cross-sectional area of the specimen. Impact strength, as defined by ASTM, refers to a material's ability to withstand sudden loads. The Charpy impact test, used in this study in compliance with ASTM A370, involves striking a notched specimen with a controlled blow to assess its ability to absorb energy before failure. This method provides valuable insights into the material's toughness under dynamic loading conditions.

Impact strength, according to ASTM standards, refers to a material's capacity to endure abrupt forces. In this research, the Charpy impact test, in accordance with ASTM A370, is employed. This dynamic assessment entails impacting a V-notched specimen with a pendulum until it fractures, and the impact strength is determined using the following equation:

$$\text{Impact strength} = (mg(h_1-h_2))/A = WRg(\cos\alpha-\cos\beta) \tag{2}$$

Where m is the pendulum mass, g is gravitational acceleration, h_1 and h_2 are the initial and final pendulum heights, A is the specimen's cross-sectional area, and α and β are the angles of fall and rise, respectively.

The hardness of the 4 different reinforced composite material specimens will be determined using a Rockwell Hardness Testing Machine. For measuring the hardness, we used scale L and the indenter diameter was 5mm. The load was 60 kgf and the dial was red.

2.8 Analytical Analysis

The Young's modulus of the whole composite is calculated by the following equation which is theoretical findings that is used for comparison with experimental findings.

$$E_c=(1-V_m)E_f + E_mV_m \tag{3}$$

Where, V_m is the matrix volume fraction which is the ratio of thickness of matrix and the thickness of whole composite. The density of the whole composite is calculated theoretically by the following equation that is also used for comparison with experimental values.

$$\rho = (\rho_f \times v_f) + \rho_m(1-v_f) \quad (4)$$

Where, ρ is the density of the whole composite, ρf is the density of fiber, ρ_m is the density of the matrix and v_f is the volume fraction of fiber which is the ratio of the thickness of fiber and the thickness of whole composite.

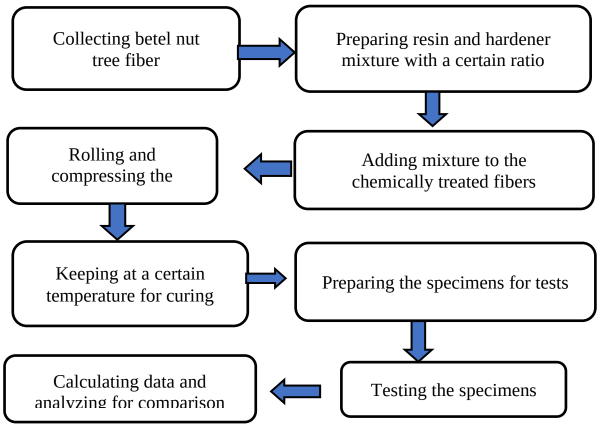
2.9 Fabrication of Natural Fiber Composite

A betel nut fiber reinforced composite was fabricated using hand lay-up molding. The process involved applying a resin mixture with hardener onto a waxed mold surface, followed by fiber layers, with repetition until the desired specimen size was reached. A 30 kg load was applied for 24 hours to remove excess resin, resulting in a betel nut epoxy composite. Four specimens with varying fiber content percentages at a fixed orientation were prepared, as detailed in Table 1.

Table 1 Different percentage of fiber content in composite

Specimen	Fiber Content (wt%)	Orientation
Specimen – C05	5	0°
Specimen – C10	10	9°
Specimen – C15	15	0°
Specimen – C20	20	0°

The following flowchart demonstrates how the process will be executed.



The fabricated betel nut composites are shown in the following fig.1.

3. Data Collection

A set of procedures are taken during the data collection process to systematically acquire data for analysis and decision-making.

3.1 Tensile and impact testing of specimens

Tensile and impact tests were conducted to evaluate the mechanical properties of test specimens. Using a Universal Testing Machine, a tensile test was performed on a specimen measuring 165 mm × 9 mm × 5 mm, with the load gradually increased.

(a) (b)

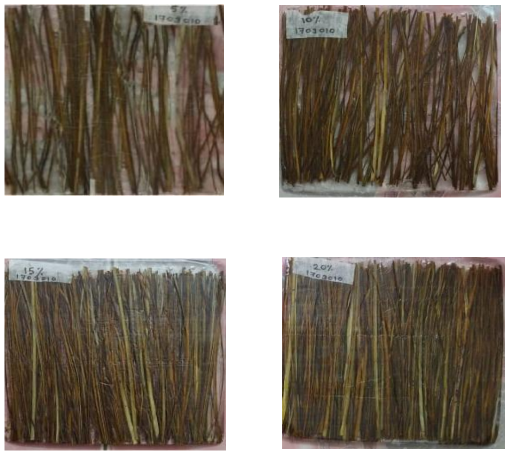


Fig.1 Fabricated specimens (a) C05, (b) C10, (c) C15, (d) C20

The average load was determined by precisely measuring the initial and final lengths of the specimen. For the impact test, a Pendulum Impact Tester (Model: HSM41) was utilized with a pendulum mass of 60 kg. The Charpy impact test method was applied to a specimen measuring 55 mm × 10 mm × 10 mm with a 2 mm V-notch, and the absorbed energy was calculated in joules. These properties of composites are shown in Table 2.

Table 2 Tensile and Impact properties of composites.

Comp-osites	Load (KN)	Area (mm^2)	Strength (MPa)	Impact Energy (Joule)	Impact Strength (J/cm^2)
Specimen C05	1	77	12.98	11.50	14.40
Specimen C10	0.75	36.8	20.38	11.70	14.60
Specimen C15	1.40	78.4	17.85	12.40	15.15
Specimen C20	1.40	81	17.28	13.40	16.81

3.3 Evaluation of mechanical properties

The Rockwell hardness test was performed using a 5 mm diameter indenter with a preload of 60 kgf, and hardness values were directly read from the red scale. The composite thickness was 5 mm, with theoretical Young's Modulus values of 1.23 GPa for betel nut fiber and 3.5 GPa for epoxy resin used to estimate the modulus of various specimens. Experimental value of Young's modulus was calculated from experimental stress and strain of the composites and experimental Young's modulus of whole composite for different specimens. Moreover, density was determined by measuring the mass and volume of rectangular specimens, with dimensions (length, width, and thickness) precisely recorded. All of these calculated values are presented in table 3.

Table 3 Mechanical properties of whole composite

Composites	Rockwell Hardness (HBL)	Young's modulus (GPa)	Density (Kg/m^3)
Specimen C05	51	1.32	1253.91
Specimen C10	25	2.06	1277.50
Specimen C15	21	4.36	1319.60
Specimen C20	17	4.60	1350.50

4. Result and Discussion

4.1 Tensile Property

From the tensile test reading, the tension load and respective area of each composite has been calculated.

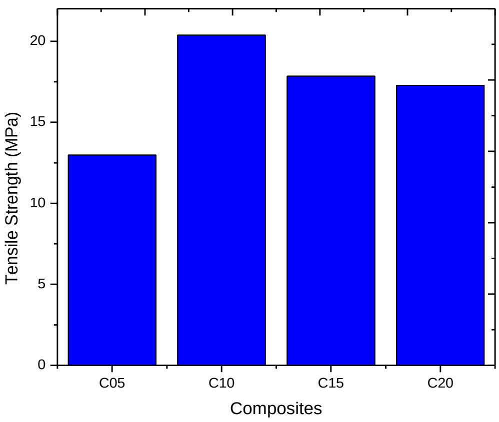


Fig.2 Variation of tensile strength on the fiber percentages.

The tensile strength of different composite specimens with varying fiber percentages is shown in Fig. 2. It was observed that tensile strength increases with fiber content up to a certain level, after which it decreases. The maximum tensile strength, 20.38 MPa, was found in the C10 composite, while the minimum, 12.98 MPa, was in the C05 composite. The C15 composite showed a tensile strength of 17.85 MPa, and the C20 composite exhibited a slight decrease to 17.28 MPa, a reduction of 3.19%. Notably, the tensile strength increased by 57% from C05 to C10, indicating that the C10 composite offers the most favorable fiber percentage for optimal mechanical properties.

4.2 Impact Properties

The impact strength of various types of specimens has been tested. The impact strength is increased by increasing the fiber percentage. In this bar chart, the impact strength is shown 14.40 J/cm^2, 14.60 J/cm^2, 15.15 J/cm^{2}and 16.80 J/cm^2 respectively for specimen C05, C10, C15 and C20. Among all specimens C20 has the highest value which is 16.80 J/cm^2. Betel nut fiber has a positive impact on impact strength. Impact strength has been increased up to C20 and for the C20 composite, the impact strength has the greatest value which is 16.80 J/cm^2.

From this bar chart, it is observed that from C05 to C10 composites, impact strength has been increased 1.39 % and from C15 to C20 the value has been increased 10.89 %. From this, it can be said that the increased fiber content is influencing the impact strength from C15 to C20 composites.

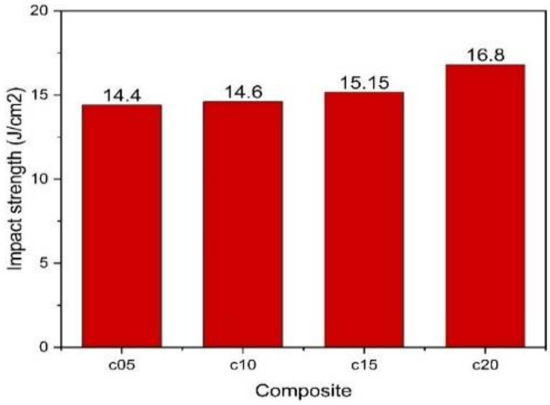


Fig.3 Variation of impact strength on the increase of fiber content.

4.3 Hardness Number

Hardness is a material's resistance to localized plastic deformation.

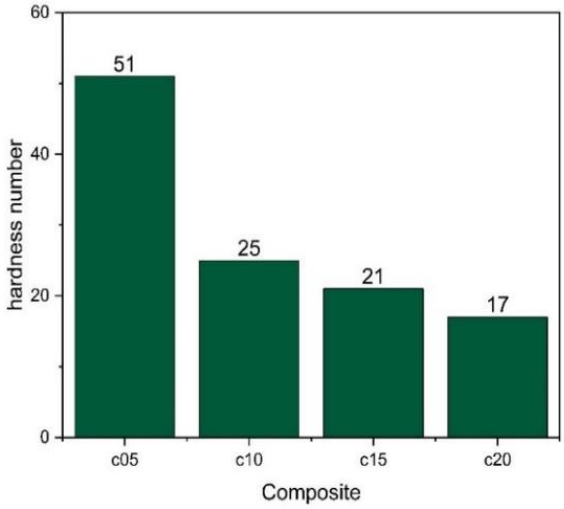


Fig.4 Variation of hardness number on the increase of fiber content

The fig.4 compares four fiber percentages based on Rockwell hardness, measured using the Rockwell Hardness Tester Machine. The maximum hardness is 51 HBL for C05 composite, while the minimum is 17 HBL for C20 composite. C10 composite has 25 HBL and C15 21 HBL. From C05 to C20 composites, hardness decreases by 66.67%, indicating that increasing fiber content in betel nut composite material decreases hardness.

4.4 Young's Modulus of Composite

Variation of young's modulus of the whole composite with fiber content are shown in fig.5. In this chart, the lower fiber content shows lowest Young's modulus compared to other specimens. Here also seen that young's modulus is increasing by increasing the fiber content in composite material. From this graph it is seen that the maximum value of Young's modulus at 4.60 GPa at C20 specimen and the minimum value at 1.32 GPa at C05 specimen.

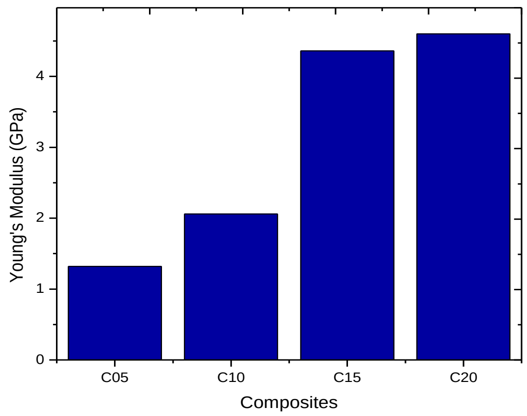


Fig.5 Variation of young's modulus on the increase of fiber content

4.5 Density of Different Composites

Fig.6 shows the variation of density on the increase of fiber content. From this bar chart, it can be observed that the maximum value of density was found 1350.50 Kg/m^3 for C20 composite and the minimum value of density was found 1253.91 Kg/m^3 for C05 composite.

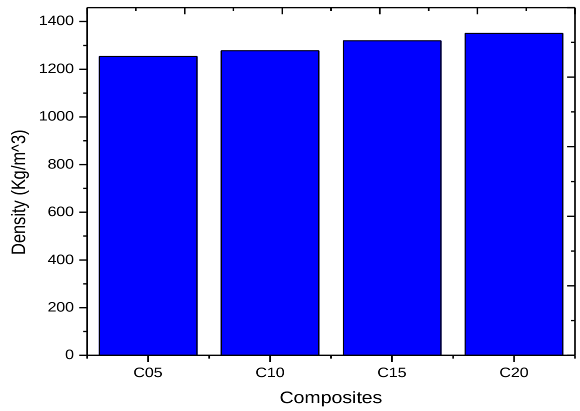


Fig.6 Variation of density on the increase of fiber content

For C10 composite it was found 1277.50 Kg/m^3 and for C15 composite it was found 1319.60 Kg/m^3. From this bar chart, it is seen that the value of density for different fiber percentages is increasing on the increase of fiber content in composite materials. From this bar chart, it is also observed that density increased 1.88 % from C05 to C10 composites and increased 7.15 % from C05 to C20 composites. From these values, it can be said that C05 composite is the lightweight composite in comparison to C10, C15 and C20 composites.

4.6 Analytical Analysis

Analytical analysis of composite materials uses mathematical models and equations to examine their mechanical characteristics, simplifying complex behavior. Experimental testing and validation are needed to confirm model accuracy and consider non-linear or non-homogeneous behavior. The Comparison of Young's Modulus is shown in fig.7.

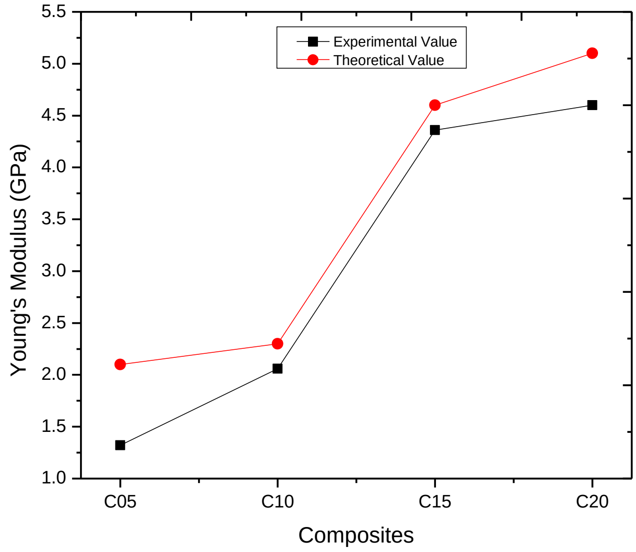


Fig.7 Comparison of Young's Modulus between experimental and theoretical values

The study compares theoretical and experimental young's modulus values, revealing that experimental values are slightly lower than theoretical ones. Young's modulus increases with fiber content, and the variation between experimental and theoretical values from C10 to C15 composites is minimal. Both values show increasing values with increasing fiber content.

Fig.8 compares experimental and theoretical density values of composites. Theoretical values are derived from whole composite density equations, while experimental values are determined from composite mass and volume. A rectangular specimen of different composites is selected for experimental value.

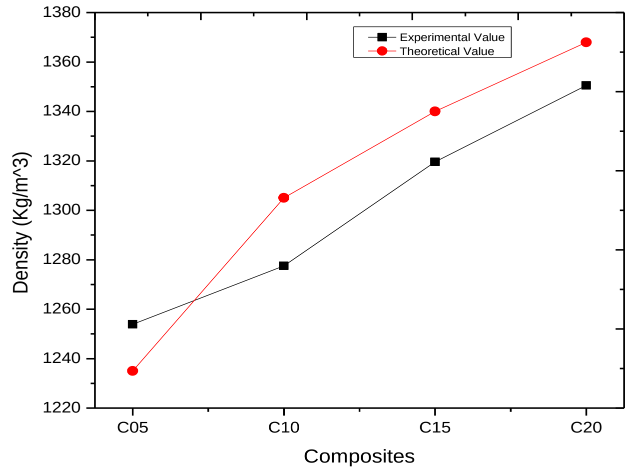


Fig.8 Comparison of density between experimental and theoretical values.

In this graph, it is shown that the density of the composite is increasing on the increase of fiber content in both experimental and theoretical values. From this graph, it is observed that the experimental value for C05 composite is higher than the theoretical value and for other composites the experimental values are lower than the theoretical values.

5. Conclusion

The development of natural fiber reinforced composites, which use lingo-cellulosic materials as reinforcing filler and thermoplastic polymers as matrix, has gained interest due to their lightweight, biodegradable, and adequate mechanical properties. Betel nut leaves, a biodegradable material, have potential as reinforcement in polymer composites. This study uses epoxy resin due to its good mechanical properties and performs alkali treatment on betel nut leaves fiber. The results show that C10 composite has higher tensile strength, C05 composite has higher hardness, and C20 composite has higher impact strength. The C10 composite has the most suitable mechanical properties with the appropriate fiber content, indicating that betel nut leaves fiber significantly impacts the mechanical properties of epoxy composites.

References

[1] S. Baladivakar, M. S. Starvin, and J. B. Raj, "Performance Evaluation of Natural Composites Made from Banyan and Cotton Fibers for Sustainable Thermal Insulation Applications," *Journal of Natural Fibers*, vol. 20, no. 1, Apr. 2023.

[2] I. Elfaleh *et al.*, "A comprehensive review of natural fibers and their composites: An eco-friendly alternative to conventional materials," *Results in Engineering*, vol. 19, p. 101271, Sep. 2023.

[3] R. Ramasubbu and S. Madasamy, "Fabrication of Automobile Component Using Hybrid Natural Fiber Reinforced Polymer Composite," *Journal of Natural Fibers*, vol. 19, no. 2, pp. 736–746, Feb. 2022.

[4] L. Yusriah, S. M. Sapuan, E. S. Zainudin, and M. Mariatti, "Characterization of physical, mechanical, thermal and morphological properties of agro-waste betel nut (Areca catechu) husk fibre," *J Clean Prod*, vol. 72, pp. 174–180, Jun. 2014.

[5] A. Lotfi, H. Li, D. V. Dao, and G. Prusty, "Natural fiber–reinforced composites: A review on material, manufacturing, and machinability," *Journal of Thermoplastic Composite Materials*, vol. 34, no. 2, pp. 238–284, Feb. 2021.

[6] H. Sharma *et al.*, "Critical review on advancements on the fiber-reinforced composites: Role of fiber/matrix modification on the performance of the fibrous composites," *Journal of Materials Research and Technology*, vol. 26, pp. 2975–3002, Sep. 2023.

[7] S. R. Djafari Petroudy, "Physical and mechanical properties of natural fibers," in *Advanced High Strength Natural Fibre Composites in Construction*, Elsevier, 2017, pp. 59–83.

[8] M. Ramesh, "Hemp, jute, banana, kenaf, ramie, sisal fibers," in *Handbook of Properties of Textile and Technical Fibres*, Elsevier, 2018, pp. 301–325.

[9] N. Karthi, K. Kumaresan, S. Sathish, S. Gokulkumar, L. Prabhu, and N. Vigneshkumar, "An overview: Natural fiber reinforced hybrid composites, chemical treatments and application areas," *Mater Today Proc*, vol. 27, pp. 2828–2834, 2020.

[10] B. Wang, S. Panigrahi, L. Tabil, and W. Crerar, "Pre-treatment of Flax Fibers for use in Rotationally Molded Biocomposites," *Journal of Reinforced Plastics and Composites*, vol. 26, no. 5, pp. 447–463, Mar. 2007.

[11] A. Hasan, M. S. Rabbi, and Md. Maruf Billah, "Making the lignocellulosic fibers chemically compatible for composite: A comprehensive review," *Cleaner Materials*, vol. 4, p. 100078, Jun. 2022.

[12] A. K. Mohanty, M. Misra, and L. T. Drzal, "Surface modifications of natural fibers and performance of the resulting biocomposites: An overview," *Compos Interfaces*, vol. 8, no. 5, pp. 313–343, Jan. 2001.

[13] E. Jayamani, S. Hamdan, M. R. Rahman, and M. K. Bin Bakri, "Investigation of Fiber Surface Treatment on Mechanical, Acoustical and Thermal Properties of Betelnut Fiber Polyester Composites," *Procedia Eng*, vol. 97, pp. 545–554, 2014.

[14] C. G. Prabhakar, K. Anand Babu, P. S. Kataraki, and S. Reddy, "A review on natural fibers and mechanical properties of banyan and banana fibers composites," *Mater Today Proc*, vol. 54, pp. 348–358, 2022.

[15] U. Sharan Gupta *et al.*, "Study on the effects of fiber orientation on the mechanical properties of natural fiber reinforced epoxy composite by finite element method," *Mater Today Proc*, vol. 45, pp. 7885–7893, 2021.

[16] M. Ho *et al.*, "Critical factors on manufacturing processes of natural fibre composites," *Compos B Eng*, vol. 43, no. 8, pp. 3549–3562, Dec. 2012.

[17] A. Lotfi, H. Li, D. V. Dao, and G. Prusty, "Natural fiber–reinforced composites: A review on material, manufacturing, and machinability," *Journal of Thermoplastic Composite Materials*, vol. 34, no. 2, pp. 238–284, Feb. 2021.

[18] X. Chen, Y. He, and Y. Deng, "Chemical Composition, Pharmacological, and Toxicological Effects of Betel Nut," *Evidence-Based Complementary and Alternative Medicine*, vol. 2021, pp. 1–7, Aug. 2021.

[19] G. M. Arifuzzaman Khan, S. R. Shahrear Palash, M. Shamsul Alam, A. K. Chakraborty, M. A. Gafur, and M. Terano, "Isolation and characterization of betel nut leaf fiber: Its potential application in making composites," *Polym Compos*, vol. 33, no. 5, pp. 764–772, May 2012.

[20] H. Sukanto, W. W. Raharjo, D. Ariawan, J. Triyono,and M. Kaavesina, "Epoxy resins thermosetting for mechanical engineering," *Open Engineering*, vol. 11, no. 1, pp. 797–814, Jul. 2021.