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EVALUATION OF TENSILE AND FLEXURAL BEHAVIOR OF EPOXY COMPOSITES REINFORCED WITH BANYAN BARK FIBERS: OPPORTUNITIES AND LIMITATIONS

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ABSTRACT

The increasing interest in sustainable composite materials has prompted the exploration of natural fibers as alternative reinforcements in polymer matrices. This study investigated the tensile and flexural behavior of epoxy-based composites reinforced with ficus benjamina bark fibers, a lignocellulosic material with previously limited utilization. The fibers were extracted from ficus bark using mechanical and alkali treatments, then incorporated into the epoxy matrix via hand lay-up method at fiber volume fractions of 15%, 20%, and 25%. Tensile and bending tests were performed in accordance with ASTM D3039 and ASTM D790. The results showed significant variations in mechanical properties with variations in fiber content. The highest performance was observed at 25% fiber volume, with tensile strength and modulus reaching 26.0 MPa and 1,841 MPa, while flexural strength and modulus reached 57.5 MPa and 2,947 MPa. This study highlights the potential and constraints of using banyan bark fiber in biocomposites. This study provides a scientific basis for further optimization of fiber-epoxy systems and emphasizes the importance of material selection and processing in the development of environmentally friendly composites.

Keywords: Banyan bark fiber, Epoxy composite, Mechanical properties.

I. INTRODUCTION

The use of polymer-based composite materials has grown rapidly in recent decades, along with the increasing need for lightweight, strong, and cost-efficient materials for various structural and non-structural applications. Among the various types of polymer matrices, epoxy resins stand out due to their superior mechanical and thermal characteristics, including high tensile strength, corrosion resistance, and good adhesion to various types of reinforcements [1]. In response to environmental issues and the need for more sustainable materials, the use of natural fibers as reinforcements in composites has become an area of increasing research attention. Natural fibers offer advantages such as abundant availability, low production costs, good biological degradation, and a relatively small carbon footprint when compared to conventional synthetic fibers [2]. Various types of natural fibers such as ramie, kenaf, sisal have been widely studied and proven to have the potential to improve the mechanical properties of polymer composites [3]. However, the potential of other local resources that have not been widely explored, such as fibers from the bark of the banyan tree (Ficus benjamina), still holds great potential for further study. The utilization of these fibers is not only in line with the renewable resource-based approach, but also has the potential to support the development of environmentally friendly and applicable local composite materials.

Although the trend of using natural fibers as composite reinforcements continues to increase, not all types of fibers show consistent mechanical performance when combined with polymer matrices, especially epoxy resins. Variations in chemical composition, microstructure, fiber length, and fiber-matrix interfacial interactions are often determining factors for the success of reinforcement [4]. In this context, banyan tree bark fiber is a natural material that has not been widely studied, both in terms of its intrinsic characteristics and its ability to strengthen epoxy composites. The absence of adequate experimental data on the mechanical behavior of these fibers in composite systems creates uncertainty in determining the feasibility of their application. Moreover, it is not yet clearly known how variations in the volume fraction of banyan bark fibers affect the tensile and flexural properties of the resulting epoxy composites. Therefore, there is an urgent need to conduct a systematic evaluation of the main mechanical parameters of these fiber-based composites in order to assess the potential and limitations of their application in the development of locally resource-based composite materials.

This study specifically aims to evaluate the effect of variations in the volume fraction of banyan bark fiber on the mechanical properties of epoxy resin-based composites. The two main parameters analyzed are tensile strength and flexural strength, as well as the accompanying elastic modulus, which represents the material's capacity to withstand static loads longitudinally and transversely. By varying the fiber volume fraction at three different levels, namely 15%, 20%, and 25%, this study attempts to identify the optimum conditions that can provide a balance between increasing mechanical strength and homogeneity of the composite structure. This evaluation is expected to provide a deeper understanding of the mechanical behavior of epoxy composites reinforced with unconventional natural fibers, as well as mapping the opportunities and limitations of using banyan bark fibers in lightweight engineering material applications. The results of this study are also expected to be the initial foundation for further development of local resource-based composite materials that support the principle of sustainability.

Although the trend of using natural fibers as reinforcements in composite materials continues to grow, there are still limitations in the scope of fiber types and matrix systems that are evaluated in depth [5]. In several previous studies, including our own, banyan bark fibers have been used as reinforcements in vinylester and polyester resin-based composites, focusing on tensile and flexural strength characteristics [6] [7] [8].. These results provide an important initial basis in identifying the potential of these fibers, but have not provided a comprehensive picture of the behavior of banyan bark fibers in different matrix systems, especially in epoxy resins that have superior mechanical properties compared to polyester and vinylester. To date, there has been no comprehensive report evaluating the mechanical performance of epoxy composites reinforced with banyan bark fibers, especially regarding the effects of varying fiber volume fractions on tensile and flexural strengths. This gap indicates a relevant knowledge gap to be bridged through a systematic experimental approach to understand the fiber–matrix interfacial interactions, as well as to objectively evaluate the potential and limitations of these fibers when combined with epoxy matrices.

This study offers an original contribution by exploring the use of banyan bark fibers as reinforcements in epoxy resin-based composites, a matrix system that is significantly different from the vinylesters and polyesters that we have studied previously. The uniqueness of this study lies in the selection of epoxy resin which is known to have superior mechanical strength and interfacial adhesion properties, thus providing a new context in assessing the effectiveness of reinforcement by natural fibers that are not commonly used. In addition, systematic variations in fiber volume fractions allow for more precise mapping of the material's mechanical response, while identifying the optimum performance point and the limits of its reinforcement efficiency. This approach not only expands the database of local natural fiber-based composite materials, but also provides critical information regarding the compatibility of banyan bark fibers with various types of polymer matrices. The scientific justification of this study lies in its efforts to fill the untapped knowledge gap, enrich the literature on sustainable materials, and support innovation in bioresource-based material technology that is more contextual and applicable in local and global environments.

II. METHODOLOGY

This study used a laboratory experimental approach to evaluate the effect of variations in the volume fraction of banyan tree bark fiber on the mechanical properties of epoxy matrix-based composites. Three variations in the volume fraction of fiber used were 10%, 15%, and 20%. The main parameters analyzed included tensile strength, elastic modulus, flexural strength, and flexural modulus. Testing was carried out following the ASTM D3039 and ASTM D790 standards for tensile and flexural tests. A brief summary of the experimental process flow is presented in Figure 1.

The main material used is banyan tree bark (Ficus benjamina) taken from trees that are more than 10 years old. The fiber extraction process begins with taking the bark from the tree trunk, then soaking it in clean water for 24 hours to soften the inter-fiber binding tissue [9]. After the soaking process, the bark is beaten using a rubber hammer to release the inter-fiber bonds and combed with a plastic comb until individual fibers are obtained. The separated fibers are then cut into a fixed size of 1 cm to maintain uniform distribution in the matrix. To improve the bond between the fiber and the matrix, chemical treatment is carried out through an alkalization process. The fibers are soaked in a 1% NaOH solution for 1 hour in a plastic container to remove dirt, lignin, and other amorphous compounds. After treatment, the fibers are rinsed with water until the pH is neutral [10] and dried in the sun.

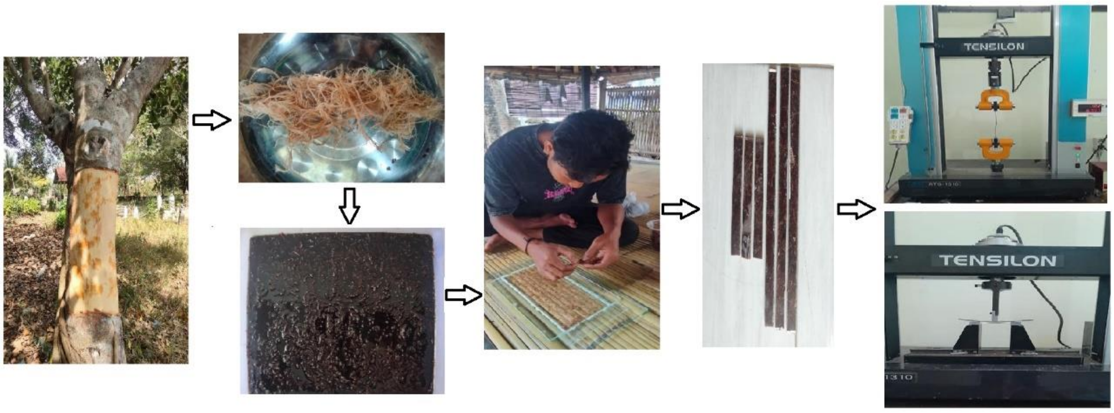

Figure 1: Experimental process flow

The composite is made using the hand lay-up technique. The matrix consists of epoxy resin mixed with cycloaliphatic amine hardener in a mass ratio of 2:1 according to the manufacturer's specifications. The mold is made of glass with dimensions of 300 mm × 140 mm and a thickness of 3 mm, including the mold base which also uses glass material to produce a smooth and flat composite surface. For each variation of fiber volume fraction (15%, 20%, and 25%), the amount of fiber and resin weighed precisely using a digital scale. The dry fibers are mixed into the epoxy resin and stirred in a glass container until the fibers are evenly distributed. Next, the hardener is added to the mixture, and the mixture is homogenized again before being poured into the mold. The curing process is carried out at room temperature for 24 hours without additional external pressure or heat. After curing is complete, the composite panel is removed from the mold and cut using a high-speed precision cutter.

The molded composite panels are cut into tensile and flexural test specimens using standard dimensions. Tensile test specimens were made with dimensions of 200 mm in length, 15 mm in width, and 3 mm in thickness, in accordance with the ASTM D3039 standard. Flexural test specimens were cut with dimensions of 90 mm in length, 15 mm in width, and 3 mm in thickness, following the ASTM D790 standard. Mechanical testing was carried out using a Tensilon RTG 1310 universal tensile testing machine. Data obtained from the test included maximum tensile strength, modulus of elasticity (Young's modulus), flexural strength, and flexural modulus. The test data were analyzed to evaluate the effect of fiber volume fraction on the mechanical performance of the composite. The measured parameters were compared between variations in fiber volume fraction to identify the optimal composition that produces the best mechanical properties. In addition, the analysis was carried out to examine the relationship pattern between fiber content and the increase or decrease in tensile and flexural strength, as well as to evaluate the potential and limitations of using banyan tree bark fiber as an epoxy composite reinforcement.

III. RESULTS AND DISCUSSION

The tensile test results show that pure epoxy resin (without reinforcing fiber) has an average tensile strength of 41.23 MPa and an elastic modulus of 1,900 MPa. When banyan tree bark fiber is added to the matrix with a volume fraction of 15%, there is a significant decrease in tensile strength to an average of 13.17 MPa and an elastic modulus of 1,008 MPa. The addition of fiber up to 20% shows a slight increase with an average tensile strength of 18.67 MPa and an elastic modulus of 1,475 MPa. Figure 2 shows the best tensile performance obtained at a volume fraction of 25% with an average tensile strength of 26.0 MPa and an elastic modulus of 1,841 MPa, which is close to the modulus value of pure epoxy.

In the bending test, the unreinforced epoxy resin showed an average bending strength of 64.2 MPa and a bending modulus of 2,839 MPa. Similar to the pattern in the tensile test, the addition of fiber at a fraction of 15% caused a drastic decrease in the bending strength and modulus to 31.1 MPa and 1,122 MPa respectively. The fraction of 20% showed inconsistency in bending performance with an average strength of 35.1 MPa and a modulus of 1,615 MPa. However, at a fraction of 25%, there was a significant increase in bending performance

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with a strength reaching 57.5 MPa and a bending modulus of 2,947 MPa (Figure 3), surpassing pure epoxy in several replications.

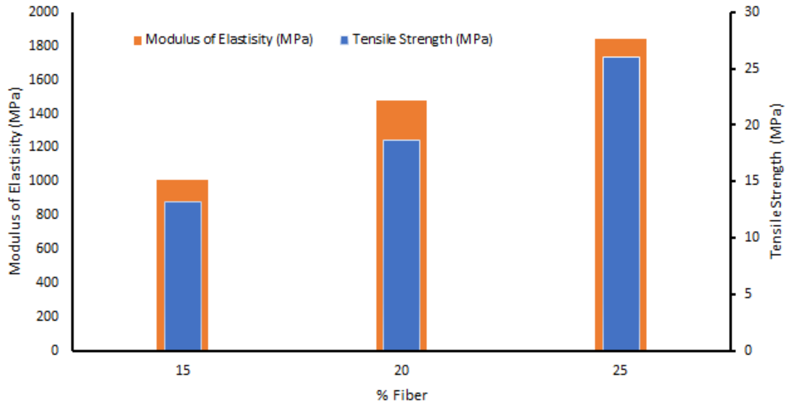

Figure 2: Tensile strength and elastic modulus of composites against fiber volume fraction

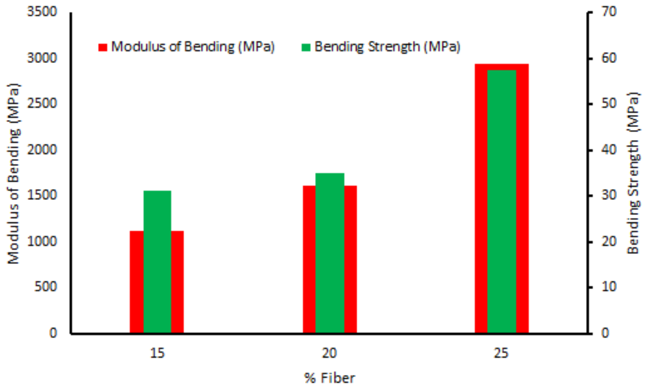

Figure 3: Bending strength and bending modulus of composites against fiber volume fraction.

Statistical analysis using one-way ANOVA was carried out to evaluate the significance of the differences between variations in fiber volume fractions on tensile and bending strengths [11]. The processing results showed that the F-calculation value was greater than the F-table at a significance level of 0.05, indicating that variations in fiber volume fractions had a significant effect on the mechanical strength of the composite. The p value <0.05 for all strength and modulus parameters, both tensile and flexural, also confirmed the statistically significant effect on composite performance due to the addition of banyan fiber.

The non-linear trend identified from the data showed that the addition of banyan fiber did not immediately increase the composite strength directly. At low fractions (15–20%), the strength decreased due to the possibility of inhomogeneous fiber distribution and weak interfacial bonds between the fiber and the matrix. However, at a fraction of 25%, there was better synergy between the fiber and the resin, allowing for more effective load transfer [12]. This suggests that there is an optimal volume fraction at which the mechanical properties of the composite can be maximized.

The relationship between fiber volume fraction and mechanical performance exhibits a parabolic behavior: low fractions tend to decrease strength due to insufficient effective load distribution, while high fractions approach or exceed the performance of pure epoxy due to increased stress transfer efficiency. However, the performance is highly dependent on the quality of the fiber dispersion, fiber length, and interfacial bonding, all of which are crucial factors in the success of natural fiber-based composite systems [13] [14].

The findings of this study provide an important contribution to the theoretical understanding of the mechanical behavior of natural fiber-based composites, especially ficus bark fibers, in an epoxy matrix. The results show that increasing the fiber volume fraction does not linearly increase the mechanical properties of the composite. This challenges the general assumption in the literature that increasing fiber content will automatically increase the tensile and flexural strength of the composite. In fact, at too low a fiber fraction (15–20%), mechanical performance tends to decrease due to phase imbalance and weak interfacial adhesion. However, at a fraction of 25%, a significant increase in tensile and flexural strength indicates that there is a critical threshold at which fibers begin to contribute effectively to load transfer. In practice, these results broaden the horizon of environmentally friendly composite material applications in engineering and industry. Ficus bark fibers, which have not been widely explored so far, have proven to have potential as an economical and sustainable natural reinforcement material for lightweight structural composites. Composites with optimal fiber fractions can be used in non-structural applications such as vehicle interior panels, lightweight household furniture, and secondary building components that do not experience extreme loads [15].

On the other hand, a better understanding of the mechanical behavior and processing limitations of these composites can support the design of more efficient biomaterial-based products, as well as serve as a reference in the development of technical standards and engineering formulations for the use of natural fiber materials in modern manufacturing industries. Although this study provides new insights into the effect of the volume fraction of banyan bark fibers on the mechanical properties of epoxy composites, there are several limitations that need to be considered. First, the distribution and orientation of the fibers in the matrix have not been uniformly controlled due to the fabrication method. Second, the imperfection of the interfacial bond between the fibers and the epoxy matrix as reflected in the low tensile and flexural strengths of the composite specimens with fiber fractions of 15% and 20%. Third, the absence of microstructural characterization on the fracture surface limits the interpretation of the failure mechanism of the composite. In addition, the alkali treatment used in this study is simple and not systematically optimized to maximize the chemical affinity between the fibers and the matrix. This study also does not examine the effects of other parameters such as fiber size, fiber orientation, which can have a significant effect on the final performance of the composite. The results of this study need to be interpreted carefully and become the initial basis for a more in-depth study at the advanced research stage.

Based on the findings and limitations of this study, there are a number of important recommendations for future research directions. First, it is necessary to develop and optimize fiber treatment methods, both in terms of NaOH solution concentration, soaking duration, and other surface activation methods, such as silanization or the use of coupling agents, to improve fiber and matrix interfacial adhesion [16] [17]. Second, exploration of more precise fabrication techniques such as vacuum infusion or compression molding can improve fiber distribution homogeneity and reduce internal defects that contribute to decreased mechanical strength [18] [19] [20]. Third, it is important to examine the effect of fiber orientation, varying fiber lengths, and the combination of natural fiber hybridization with synthetic fibers as a strategy for engineering the mechanical performance of composites. In addition, microstructural analysis using scanning electron microscopy (SEM) and thermal characterization such as TGA or DSC will enrich the understanding of chemical interactions and material failure mechanisms.

The use of banyan bark fiber as an epoxy composite reinforcement offers technical potential as an alternative material, contributing to economic and environmental aspects. The use of biomass waste such as banyan bark which has not been optimally utilized can reduce the cost of composite production, especially in non-structural or semi-structural applications. Simple fiber extraction supports a community-based production scheme that is socially and economically inclusive. From an environmental perspective, banyan bark as a renewable source has better biodegradability than synthetic fibers so that it can contribute to reducing the accumulation of non-degradable waste at the end of the product's life. However, chemical treatments such as alkalization used in the fiber processing process require attention in the management of solution waste so as not to have a negative impact on the aquatic ecosystem

IV. CONCLUSION

This study has evaluated the effect of variations in the volume fraction of banyan bark fiber on the tensile and flexural properties of epoxy resin-based composites. The test results show that the addition of fiber up to 25% by volume can increase the tensile and bending strength compared to composites with lower fiber fractions. The highest increase in tensile strength was achieved at a fiber volume fraction of 25%, with an average value of 26.0 MPa and an elastic modulus of 1,841 MPa. In the flexural test, the 25% fiber fraction also showed the most optimal performance with an average strength of 57.5 MPa and a flexural modulus of 2,947 MPa.

These findings indicate that banyan bark fiber has the potential as a natural reinforcing material in epoxy composite systems, especially at certain ratios that allow more effective stress transfer between phases. However, the overall mechanical performance is still influenced by the basic properties of the fiber which are relatively lower than the matrix, as well as the possibility of agglomeration or uneven distribution of fibers in certain fractions

V. REFERENCES

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