

Effect of a sugar palm fiber and pineapple leaf fiber reinforcement in a polyester matrix on flexural strength and macrostructural characteristics

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Abstract

The utilization of natural fiber-based composites has emerged as a promising alternative to synthetic materials because of their lightweight, high strength, and eco-friendly characteristics. This research investigates the influence of combining sugar palm fiber and pineapple leaf fiber on the flexural strength and macrostructural characteristics of polyester-matrix composites. Specimens were fabricated using the hand lay-up press technique, while flexural strength testing followed the ASTM D-790 standard. Macrostructural analysis was performed using a macro lens to evaluate fiber distribution, void presence, and delamination. The results confirmed that fiber composition significantly affected both mechanical and structural properties. Among all specimens, the pineapple-fiber-dominant composite (Specimen 5) achieved the highest flexural strength of 80 MPa, whereas the specimen with higher sugar palm fiber content (Specimen 3) showed the lowest value of 59.4 MPa. Improved performance was strongly associated with uniform fiber distribution, effective interfacial bonding, and reduced voids. Overall, the findings highlight the considerable potential of natural fibers as reinforcements for producing strong, durable, and sustainable composite materials.

Keywords:

Composite, natural fiber, polyester resin, bending, macrostructure

1 Introduction

Technological and industrial developments demand the availability of materials with superior mechanical properties while remaining lightweight and efficient. One material that addresses this challenge is composite materials, which are materials formed from two or more different components, resulting in new properties that are superior to those of the original materials[1]. Composites are widely used in various industries, such as construction, automotive, and aerospace, due to their advantages, such as light weight, strength, corrosion resistance, and malleability[2].

Currently, there is a shift from the use of synthetic fiber-based composites to the use of natural fibers as reinforcement materials. This is driven by awareness of the importance of using environmentally friendly, renewable, and economical materials [3]. Natural fibers such as sugar palm fiber and pineapple leaf fiber are examples of agricultural waste with the potential to be developed as composite reinforcement materials. These two types of fibers have distinct physical characteristics and are widely available in Indonesia [4]. Plant and agricultural fibers play an important role in agriculture by improving soil health, promoting sustainable practices, and reducing environmental impact. Fibers are biodegradable, renewable, and have a low environmental footprint, making them ideal for use as sustainable composite materials. The use of plant

fibers in composites contributes to material blending, management of easily degradable materials, and overall sustainability.

Several previous studies have examined the use of natural fibers as composite reinforcements [5], which utilized sugar palm fiber in flexural strength tests, demonstrated that the fibers could strengthen polyester resin matrices. Similarly, another research, which used pineapple leaf fibers as a material for making ship skins, demonstrated significant potential for improving the material's mechanical properties [6] [7]. However, these studies were limited to the use of a single fiber type. A problem that arises is the lack of research combining two types of natural fibers, such as sugar palm fiber and pineapple leaf fiber, in a single composite [8]. This combination, however, has the potential to create a stronger and more efficient material structure. Furthermore, the macrostructure of composites has not been widely studied. Macrostructure, which includes fiber orientation, distribution, voids, and interphase damage, plays a crucial role in determining the strength and durability of composites [9][10].

In this study aims to investigate the effect of variations in hybrid fiber blends (pineapple leaf fiber and sugar palm fibers) on mechanical properties, particularly flexural strength, and to analyze the macrostructural condition of the fracture surface of polyester-based composites to identify the level of interfacial bonding and material failure mechanisms. This research can contribute to new products made from a mixture of natural fibers and resin with the optimal fiber composition based on bending strength analysis and macrostructure and to the development of natural waste-based composite materials that are not only high-quality but also sustainable and environmentally friendly.

2 Research methodology

2.1 Experimental design

This study used a laboratory experimental approach with a hand lay-up press method to produce a polyester resin-based composite material reinforced by a combination of sugar palm fiber and pineapple leaf fiber. The composite was made in five specimen variations based on differences in fiber and resin volume fractions. Flexural strength testing was conducted to evaluate the mechanical properties of the material. Bending tests were conducted using a universal testing machine with a maximum load of 10 kN and a load precision of $\pm 0.5\%$, including the support span, loading speed, and maximum deflection applied in this test while macrostructural observations aimed to identify fiber distribution, the presence of voids, and indications of delamination in the composite structure.

2.2 Materials and tools

A. Materials used are :

1. Sugar Palm Fiber and Pineapple Leaf Fiber are obtained from mature leaves, which are then cleaned, combed, and dried along their length, then cut to a length of 150 mm and soaked in 5% NaOH to remove dirt and wax layers [8].
2. Polyester resin (Yucalac 157 BQTN-EX) is used as the matrix.
3. Methyl Ethyl Ketone Peroxide (MEKP) catalyst at 1% to accelerate resin hardening [11].

B. Tools used:

1. ASTM D-790 standard silicone mold
2. Bending Testing Machine (3-point bending test)
3. Metallurgical 4XC macro microscope
4. Vernier calipers, steel ruler, measuring cup, brush, scissors, sandpaper, digital scale, container, and stirring stick.

2.3 Research procedures

2.3.1 Specimen preparation

The preparation of specimen materials requires the following:

- a. The specimen mold is made from silicon with dimensions of 150 mm in length, 12.7 mm in width, and 5 mm in thickness.

- b. Prepare rattan fibers and pineapple leaf fibers with a length of approximately ± 20 cm.
- c. Soak the rattan fibers and pineapple leaf fibers in a 5% NaOH solution for 2 hours, then dry for 24 hours at room temperature.
- d. Weigh each material to be used for the specimen according to the specified composition.
- e. Place the resin and fibers into the mold.
- f. Close the mold tightly to prevent any voids or trapped air inside, ensuring it is complete, and wait until it dries.
- g. Remove from the mold, then cut and finish the composite gradually with sandpaper until it reaches the specified dimensions

2.3.2 Bending test

The steps for conducting research using a bending test tool, often referred to as a testing method, are as follows:

- a. Prepare the materials to be tested.
- b. Draw a marking line to determine the position of the specimen's center point.
- c. Set the load magnitude to 10 KN.
- d. Place the sample on the bending test machine with a specific distance between the support surface and the center point.
- e. Turn the handle until the load touches the specimen and the pressure gauge reads zero.
- f. Set the needle rotation to control the amount of load to be applied.
- g. Record the bending test results at each rotation as the test data.

2.3.3 Macrostructure observation

The following are the steps involved in macrostructure testing:

- a. The specimen is placed under a microscope in a horizontal position with the center as the focal point of the study.
- b. Focus and lighting are adjusted to ensure sharp and contrasting images.
- c. The image is analyzed using an Optilab camera integrated with computer software.

- d. The image is presented in digital format for more detailed macrostructure analysis.

2.3.4 Data analysis

In the next stage, the data obtained from the flexural sample tests is processed and analyzed. The following are the steps in the data analysis process:

- a. The specimen is placed under the microscope in a horizontal position with the center as the focal point of the study.
- b. Focus and lighting adjustments are performed to obtain sharp and high-contrast images.
- c. Imaging is conducted using an Optilab camera integrated with computer software.
- d. The results are presented in digital format for extended macrostructure analysis.

3 Results and discussion

3.1 Bending test results

Bending strength testing was conducted at the ATMI Surakarta Polytechnic Materials Testing Laboratory. The specimens had previously undergone macrostructural testing to determine material properties and optimize bending testing. The bending test yielded several composite samples with two types of reinforcement: sugar palm fiber and pineapple leaf fiber. Five test specimens were used, each with varying reinforcement volume fractions and variations. Three samples were used for each specimen to average the best results.

The model relationship derived from ANOVA is based on the simplified quadratic model of R_a obtained in Table 1. According to statistical analysis, the developed model is consistent with the experimental data, the model is adequate, there is no significant lack of fit, and it has satisfactory coefficients of determination for R_a and $MRR (R^2)$. Similarly, several terms were excluded from the model even though they were not significant, because maintaining the model hierarchy often ensures reasonable agreement between the 'Pred R-Squared' and 'Adj R-Squared' and thus an insignificant lack of fit. The R^2 result is 0.8588, and the Adeq Precision (AP) = 5.700. Ideally, AP should be greater than 4 as it measures the signal-to-noise ratio.

Table 1. Bending test value

No	Volume fraction (%)	Sample	Maximum load (N)	Bending strength (MPa)	Coefficient of variance
1	Sugar palm fiber 40	1	141.98	59.2	17%
	Resin 59	2	214.12	82.9	
	Catalyst 1	3	164.00	68.4	
	Average		173.36	70.1	
2	Pineapple leaf fiber 40	1	152.55	63.6	5%
	Resin 59	2	138.17	62.2	
	Catalyst 1	3	142.81	68.5	
	Average		144.51	64.7	
3	Sugar palm fiber 20	1	167.32	65.2	17%
	Pineapple leaf fiber 20	2	121.75	47.5	
	Resin 59: catalyst 1	3	160.37	65.5	
	Average		149.81	59.4	
4	Sugar palm fiber 15	1	188.16	74.9	6%
	Pineapple leaf fiber 25	2	191.32	78.5	
	Resin 59: catalyst 1	3	177.98	69.3	
	Average		185.82	74.2	
5	Sugar palm fiber 25	1	189.39	80.5	10%
	Pineapple leaf fiber 15	2	167.53	71.1	
	Resin 59: catalyst 1	3	237.41	88.4	
	Average		198.11	80	

The bending test results graph can be shown in Fig. 1. Fig. 1 shows that the relationship between volume fraction and bending strength affects the quality of each sample. Starting from a pure specimen without any mixture of sugar palm fiber and pineapple leaf fiber, to a blend of all fibers. Specimen 1 showed a flexural strength of 70.1 MPa. This is consistent with research conducted, which found that the higher the pineapple fiber composition, the higher the

bending value (reaching ~49 MPa at high fractions [12][13]. This indicates that the composite material in this sample has good mechanical performance in bending forces [14]. This can be attributed to several important factors, such as the compatibility of fiber volume with resin, internal structure, and the interaction between polyester resin and reinforcing fibers. The fibers used have the ability to be evenly distributed and oriented following the

bending stress beam, which allows them to deform effectively. This indicates that the composition in Sample 1 has been produced using good techniques, and there are not many defects, such as air voids, that can reduce the material's strength.

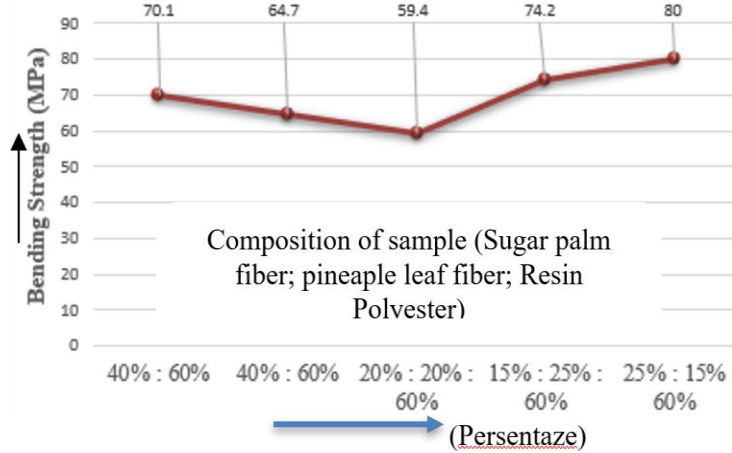


Fig. 1. Average bending strength values of composites with various fiber compositions

Specimen 2 demonstrated a flexural strength of approximately 64.7 MPa. Although lower than Sample 1, this strength is still quite good. This decrease in strength may be due to differences in fiber distribution or slight variations in resin and fiber volume. Additionally, there may be slight or uneven flexure across the material due to fiber orientation [15]. Any macroscopic potential, such as pores or air bubbles, during the resin manufacturing process can also contribute to mechanical failure. However, overall, Sample 2 still demonstrates a fairly robust composite quality and is easily applicable to relevant applications.

Furthermore, Specimen 3 had the lowest value of only 59.4 MPa, indicating that the volume composition of this specimen has consistent weaknesses, both in distribution strategy, orientation, and interphase bond quality [16]. This can be explained by the dominance of more asymmetric and heterogeneous sugar palm fibers, which also tend to create voids that lead to mechanical failure.

Specimen 4 demonstrated the highest flexural strength, with a flexural strength of 74.2 MPa. The results indicate that the composite material used in Sample 4 exhibits excellent flexural strength. This high value indicates that the reinforcing fibers used are highly effective due to the strong bond between the resin and the fibers. The

reinforcing fibers have a high capacity, are firmly embedded in the resin, are oriented parallel to the bending rays, and have no defects or voids indicating their presence. This sample can be described as the best in terms of material configuration, both in terms of volume fraction composition, mixing technique, and molding process. This illustrates the potential use of this composition for structural applications requiring high flexural tolerance.

The fifth specimen, based on the flexural test results, demonstrated the highest flexural strength at an average of 80 MPa, making it the sample with the best mechanical performance among all variations. This value indicates that the combination of pineapple leaf and sugar palm fibers in the volume frame used in this particular specimen results in a very positive interaction between the two phases. The reinforcement is firmly embedded in the polyester resin matrix with an even distribution and fiber orientation that approaches the bending loading direction, thus maximizing the drying time against bending forces.

The existing material sample illustrates the effect of fibers on its flexural strength, as shown in Fig. 1. Physical changes in the flexural strength results among specimens also occur due to the composition of the natural fiber mixture.

3.2 Macro structure test results

The purpose of the fracture cross-sectional image is to identify the failure that occurred in the composition. Furthermore, the fracture image is intended to display the yield characteristics in terms of impact and tensile toughness. The image was taken using a metallurgical microscope at 100x magnification.

3.2.1 Fiber pull-out after bending test

Voids or cuts can occur due to improper production processes, pressing, mixing, or composition techniques. Catalysts cause numerous air bubbles because the resin absorbs quickly, making it difficult for air bubbles to rise to the surface and become trapped within the composite. The purpose of pressing in the composition is to reduce air entrapment. The presence of air voids in the composition, as seen in Fig. 2, significantly reduces the composition's strength.

Fig. 2(a) shows the results of the macrostructural analysis of a composition using sugar palm fiber. The presence of clear cavities indicates that the distribution of polyester resin is not affected by the porous structure of the sugar palm fiber network. These cavities indicate a greater degree of bonding between the matrix and the fiber, which is detrimental to the overall flexural strength of the composite.

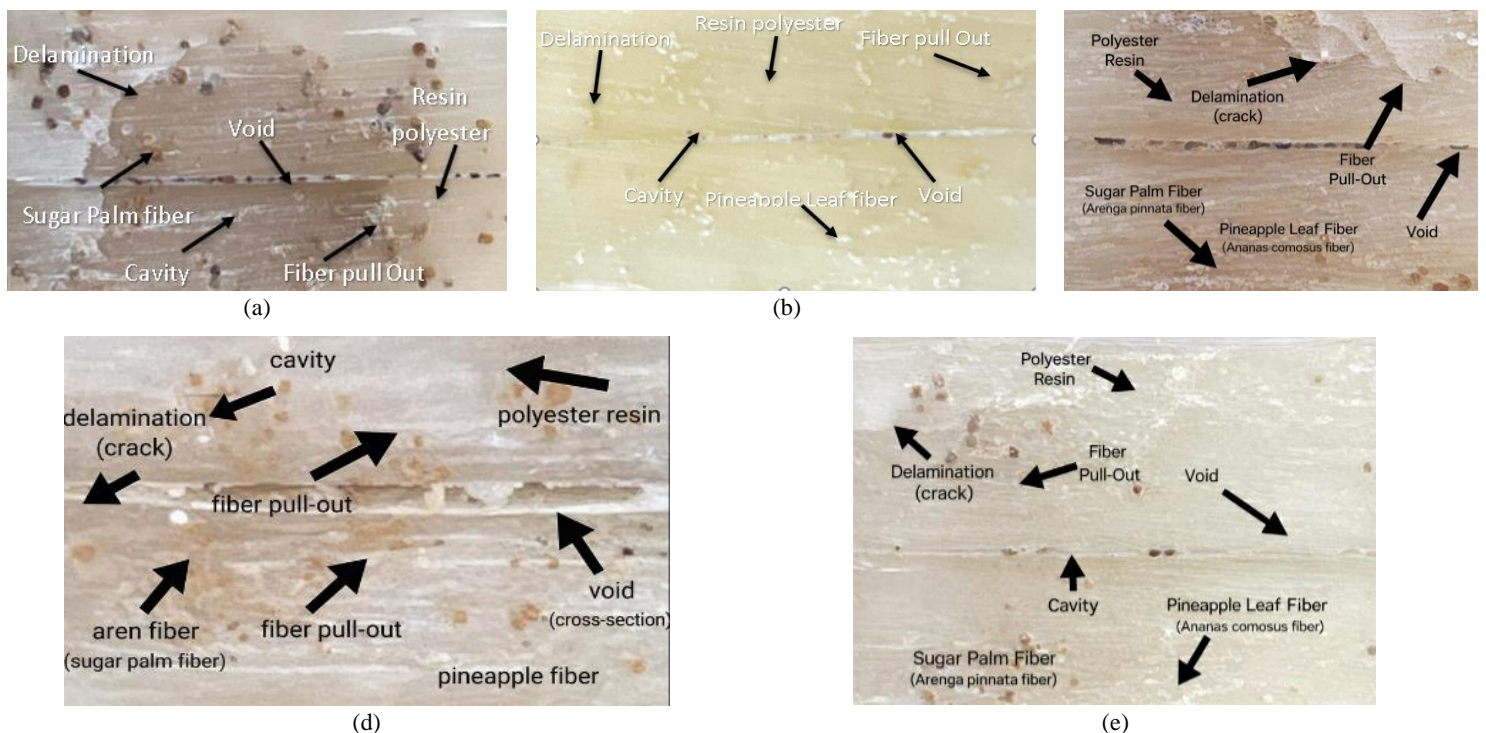


Fig. 2. Macrostructure test results of specimens 1-5 (a-e)

The more cavities present, the greater the potential for cracking and fracture during mechanical testing. Therefore, specimens with this structure consistently produce quite strong flexures.

Fig. 2(b) shows the macrostructure of the composition using pineapple leaf fiber. It can be observed that the polyester resin is more homogeneous in terms of the number of voids compared to the other specimens. The stronger and finer pineapple fibers contribute to the creation of a strong bond with the resin, resulting in superior bending results. The minimal number of voids in this structure indicates that the composition can withstand greater loads and fractures. This specimen is one of the best examples of macrostructure composition.

Fig. 2(c) depicts the microstructure of a specimen using a combination of sugar palm fiber and pineapple leaf fiber. Although some small voids remain, this composition demonstrates a very accurate fiber distribution. The presence of finer and denser pineapple fibers helps strengthen the matrix and improve material bonding. However, the sugar palm fiber structure remains porous, meaning the resin is not as pure as it should be. Overall, this specimen demonstrated better bending test results than the first due to the improved distribution of the constituent materials.

In Fig. 2(d), a composite material encasing sugar palm and pineapple leaves in polyester resin is visible. Several defects, such as voids, cavities, and cracks (delamination), can be identified as indicators that do not accurately reflect the resin distribution among the fibers. Furthermore, fiber pull-out, which occurs when the fibers are pulled out of the matrix, indicates that the bond between the resin and the fibers is not yet strong enough. However, compared to sugar palm fiber, the distribution of pineapple leaves is more favorable. Because pineapple fibers are not as effective at absorbing resin, they are more structurally stable. Conversely, sugar palm fibers, with their larger diameter and rougher texture, create voids around them, which reduce the bonding efficiency between the components.

Finally, in Fig. 2(e), the composite microstructure shows more complex defect phenomena. These can be observed as a result of delamination, internal voids, fiber pull-out, and several voids present in various areas. This indicates that during the resin penetration and soaking process, there were imperfections in the resin penetration toward the fiber network, particularly in the fiber area. Unlike the first illustration, the cracks appear to be more dominant and symmetrical in the horizontal direction. This indicates that the layers are not very strong, so when the composite is bent, the structure tends not to delaminate. The presence of voids and fiber pullout also indicates that the adhesion between the phases is not ideal.

3.3 Discussion

3.3.1 Void

Voids or cuts can occur due to improper production processes, pressing, mixing, or composition techniques. Catalysts cause numerous air bubbles because the resin absorbs quickly, making it difficult for air bubbles to rise to the surface and become trapped within the composite. The purpose of pressing in the composition is to reduce air entrapment. The presence of air voids in the composition, as seen in Fig. 3, significantly reduces the composition's strength.

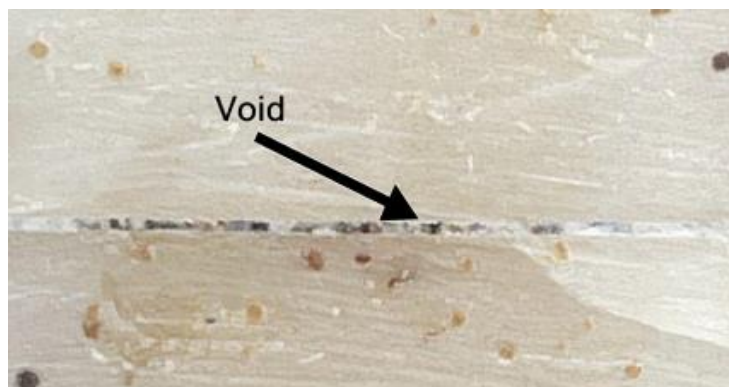


Fig. 3. Sections (void)

Quantitatively, the relationship between voids or fiber pull-out and the reduction in bending strength can be explained through the percentage of void content and stress transfer efficiency. a. Quantitative Relationship of Void Content to Strength: Voids in composites act as stress concentrators. Strength Reduction: Empirically, literature often reports that every 1% increase in void content can lead to a 5% to 10% decrease in mechanical strength (including bending and shear), b. Fiber pull-out occurs when the shear stress at the fiber-matrix interface is smaller than the stress required to break the fiber.

Quantitatively: If the fiber length is shorter than the critical length, the fiber will not break but will be pulled out. This results in the composite not reaching its maximum strength potential. Fracture Energy: Macro pull-out reduces the maximum bending stress value because the matrix fails to transfer the load to the fibers effectively, causing the load to be fully borne by the brittle polyester matrix [17][18]. The obtained Coefficient of Variation values range between 5% - 17% according to macrostructure observations; the higher the CV value, the more voids are present in the specimen.

3.3.2 Delimitation

The delamination observed in Fig. 4, where the crack propagated between the composite layers rather than directly under the loading point, indicates insufficient interlayer bonding and weak fiber-matrix adhesion [19]. This phenomenon occurs because the tensile stresses concentrated at the bottom of the specimen initiate cracks that exploit weak interfaces, allowing the fracture to spread along the fiber-resin boundaries instead of through the fiber itself.



Fig. 4. Crack (delimitation)

The presence of pectin and hemicellulose in natural fibers exacerbates this problem, as their hydrophilic nature reduces wettability with the hydrophobic polyester resin, creating voids and poor adhesion that facilitate delamination. Similar findings were reported [20], who highlighted that high hemicellulose and pectin content in natural fibers strongly contributes to interfacial debonding and delamination in composites. Furthermore, recent studies demonstrated that alkali treatment significantly improves resistance to delamination by removing hemicellulose and waxes, thereby enhancing fiber-matrix compatibility and interlayer bonding [21].

These results suggest that chemical treatment of palm and pineapple leaf fibers could reduce delamination, leading to better structural integrity and higher flexural performance of the composite.

4 Conclusion

This research demonstrates the potential of hybrid natural-fiber composites as sustainable materials for structural and semi-structural applications. The results confirm that the combination of sugar palm fiber and pineapple leaf fiber in a polyester matrix significantly affects the flexural strength and macrostructural quality of the composite. The highest flexural strength (80 MPa) was obtained in the pineapple-fiber-dominant specimen, while higher sugar palm fiber content resulted in lower strength. Macrostructural

observations indicate that uniform fiber distribution, strong fiber–matrix bonding, and minimal voids are key factors in improving flexural performance. These findings suggest that hybrid natural fibers can be used as sustainable alternatives for lightweight structural boards and composite products. Future studies should focus on fiber surface treatment, optimized fiber architecture, and improved fabrication methods.

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