Physical and Mechanical Properties of Abaca Fiber Reinforced Polymer Composites for Sustainable Structural Application

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ABSTRACT

This study evaluates the physical and mechanical properties of Abaca Fiber Reinforced Polymer (AbFRP) laminates for sustainable structural application. The research examines the impact of alkali treatment on the weight and diameter of the abaca fibers, as well as the tensile strength of both individual fibers and AbFRP laminates. The results indicate that the application of 0.5 wt% NaOH treatment reduced the weight and diameter of abaca fibers by 5.7% and 4.2%, respectively. Alkali treatment enhanced the tensile strength of single fibers, increasing it from 977.8 MPa to 1978.6 MPa, while the tensile strength of AbFRP laminates decreased from 78.1 MPa to 67.3 MPa. In terms of elastic modulus, the untreated and treated AbFRP laminates exhibited values of 14.9 GPa and 18.5 GPa, respectively. These findings demonstrate that AbFRP laminates possess notable mechanical characteristics, making them suitable for implementation for structural application.

Keywords-abaca fibers; alkali treatments; physical properties; mechanical properties; tensile strength

I. INTRODUCTION

Global awareness of environmental protection issues, particularly in the context of carbon emissions reduction and biodiversity, is consistently increasing. This aligns with Sustainable Development Goals (SDGs) regarding Climate Action, encouraging many researchers to innovate with natural materials in various fields, including civil engineering.

Natural fibers -categorized into straw, bast, leaf, seed/fruit, and grass fibers [1]- are mainly composed of cellulose, which impacts tensile strength and elasticity. With their bio-renewable and environmentally friendly properties, natural fibers can replace synthetic and harmful materials [2,3]. The biocompatibility and hydrophilic properties, which could be considered as limitations, can be effectively addressed through surface modifications using chemical processes. As a result, natural fibers are being used in composite materials with several studies exploring their mechanical characteristics [4-7].

Natural fibers, such as kenaf, flax, abaca, and hemp, have already been utilized in automotive manufacturing to produce door panels, seat backs, interior trims, and spare wheel pan [8]. Among these, jute fibers, are known for their tensile strength, durability, low cost, and biodegradability [9], are employed in the fabrication of various products, including sheets/boards, doors, furniture, window frames, railings, and other similar items [10].

Abaca fiber (Musa textilis) derived from leaf fiber, exhibits notable tensile strength, porosity, and durability in saline environments. Its chemical composition consists of 68.32% cellulose, 17.32% hemi, and 8.5% lignin. According to [11], abaca fiber has a diameter of 150-260 m, a tensile strength of 980 MPa, a modulus of elasticity of 27-32 GPa, and an elongation at break of 18-21%. Due to its low mass, abaca fiber composites have been applied in both the automotive and construction industries (Reinforced Concrete (RC), asphalt, cement, or panels).

Inspired by well-known strengthening materials, such as Carbon Fiber Reinforced Polymer (CFRP) and Glass Fiber Reinforced Polymer (GFRP) [12-15], researchers are exploring abaca fiber as an alternative material for structural repair and strengthening. However, while studies have investigated natural fibers for strengthening RC structures [16-19], there is limited research on the use of AbFRP.

II. EXPERIMENTAL PROGRAMS

A. Materials

The abaca fibers used in this study were obtained from North Sulawesi, Indonesia with an average length of approximately 3 meters. These materials were cleaned and then separated in two forms: untreated, without alkali treatment, and treated, with alkali treatment. Alkali treatment was applied to reduce abaca fiber's chemical and water content, while increasing its strength and durability.

Alkali Treatment Process

The alkali treatment involved soaking the abaca fibers in 0.5% NaOH solution for 30 minutes. After this process, they were rinsed using running water to remove any residual NaOH and then dried in an oven at 60°C for 24 hours to minimize moisture content. This technique aimed to ensure optimal adhesion between the fiber and the polymer-based adhesive. The treatment process is illustrated in Figure 1:

a) Soaking b) Rinsing c) Drying

Fig. 1. Alkali tratment process of abaca fibers.

B. Specimens

The specimens consist of single abaca fibers and AbFRP laminates. A total of 40 single fibers were prepared, consisting of 20 untreated and 20 treated fibers, to evaluate the effect of alkali treatment on the weight and diameter of the single abaca fiber. Additionally, three untreated and three treated specimens were prepared to assess the impact of alkali treatment on tensile strength, strain at break, and modulus of elasticity for both single fibers and AbFRP laminates. The AbFRP laminate was also tested using Scanning Electron Microscopy (SEM) to analyze the interaction between abaca fiber and epoxy matrix. Table I provides a summary of the testing types and the number of specimens used in each test:

TABLE I. TESTING TYPES AND NUMBER OF SPECIMENS

Testing types	Specimens	Un-treated	Treated
Weight and diameter	Single fiber	20	20
Tensile strength	Single fiber	3	3
Tensile strength	AbFRP laminates	3	3
SEM	AbFRP laminates	-	1

C. Weight and Diameter Test

In this test, the weight and diameter of abaca fibers were carried out before and after the alkali treatment process. The study employed a sample of abaca fiber consisting of 20 strands selected randomly. The weight of the fiber was determined using an analytical balance, while for the diameter measurement, a screw micrometer with a 0.01 mm accuracy was utilized. Each single fiber was measured at three different points, specifically at both the fiber's ends and center.

D. Tensile Strength Test

Tensile strength tests were conducted on both single fiber and AbFRP laminates following the ASTM D3039 of [20].

1) Single-Fiber

For tensile testing, three untreated and three treated single fibers were selected randomly from those previously tested for weight and diameter. To assist with gripping during testing, each fiber was attached to a paper grip aid with a central hole to observe the fiber's failure. As shown in Figure 2, tensile testing was performed using a Universal Testing Machine (UTM) with a capacity of 10 kN under displacement control at a rate of 1 mm/min.

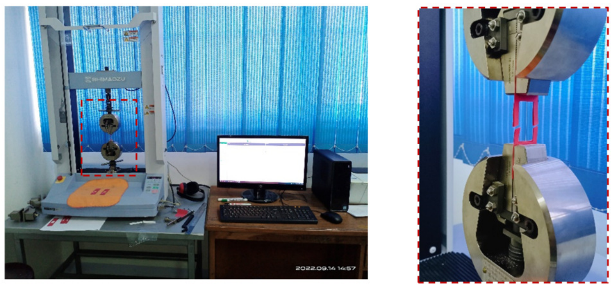

Fig. 2. Tensile strength test of single fiber.

2) Fabrication and Testing of AbFRP Laminates

The fabrication process for AbFRP laminates is depicted in Figure 3. This process involved several stages, including weighing the fibers, weaving and preparing, and applying the epoxy. Three treated and three untreated AbFRP laminates were tested using a UTM having a capacity of 1000 kN, under displacement control at a rate of 1 mm/min (Figure 4). To measure the strain in the AbFRP laminates, a strain gauge was attached at the center of each specimen.

E. SEM Test

After the tensile strength test, several specimens were taken for SEM testing on AbFRP laminates. The result of the test was used to analyze the interaction between epoxy matrix and abaca fibers.

a) Weaving process b) Epoxy application

Fig. 3. Fabrication process of AbFRP laminates.

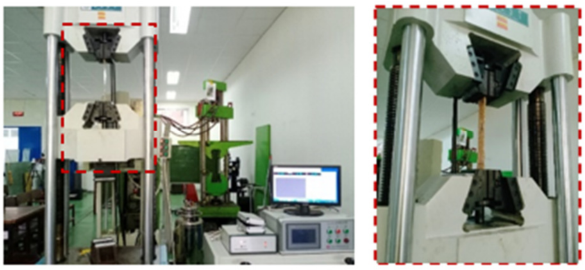

Fig. 4. Tensile strength of AbFRP laminates.

III. RESULTS AND DISCUSSIONS

A. Weight and Diameter of Single Fibers

The average weight of the 20 untreated single fibers was 0.52 g, whereas the average weight of the 20 treated single fibers was 0.55 g. These results indicate the weight of the treated fibers was approximately 5.7% lower than that of the untreated fibers. This weight reduction is attributed to the alkali treatment process, which dissolves non-cellulosic components like lignin, hemicellulose, and pectin, while under specific conditions, it can hydrolyze cellulose chains.

Figure 5 illustrates the diameter of abaca fibers randomly selected from a total of 20 untreated and 20 treated samples.

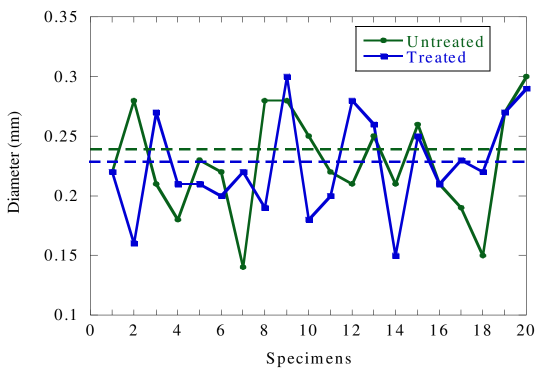

Fig. 5. Diameter of single abaca fibers.

The average diameter of the untreated fibers was 0.24 mm (240 μm), while the treated fibers had an average diameter of 0.23 mm (230 μm). This is in accordance with [21], which reported that the diameter of abaca fiber ranges from 150 to 260 μm. The observed variation in fiber diameter was significant, depending on the location of the sample within the stem. Those taken from the lower part of the stem (closer to the root), are greater in diameter than those obtained from the upper parts. The morphology of the abaca fiber cross-section is depicted in Figure 6:

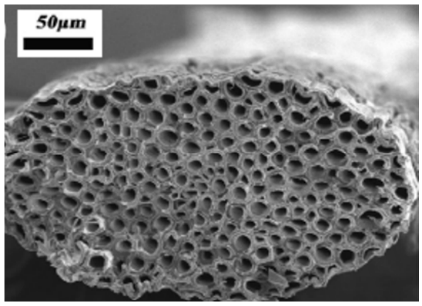

Fig. 6. Cross-sectional morphology of abaca fibers.

B. Tensile Test of Single Fibers

Table II shows the tensile test results of single abaca fibers.

TABLE II. MECHANICAL PROPORTIES OF SINGLE FIBERS

Single Fibers	Mechanical Properties				
	Diameter [mm]	**Cross Section, *A* [mm]**	**Tensile Strength, f_s [MPa]**	**Strain at Break [%]**	**Elastic Modulus, *E* [GPa]**
UT-1	0.16	0.02	1161.9	7.1	16.4
UT-2	0.20	0.03	723.9	6.3	11.5
UT-3	0.18	0.03	1037	6.5	16.9
T-1	0.12	0.01	1866.8	9.8	19.1
T-2	0.11	0.01	2100.2	10.7	19.6
T-3	0.12	0.01	1968.6	11.7	16.8

Alkali treatment had a significant impact on the mechanical properties of single abaca fibers. Untreated fibers exhibited average tensile strength of 977.8 MPa, strain at break of 6.5%, and elastic modulus of 14.9 GPa. In comparison, treated fibers displayed higher average values, with a tensile strength of 1978.6 MPa, strain at break of 10.7%, and elastic modulus of 18.5 GPa. This is consistent with a previous study, [22], which found that alkali-treated fibers had improved stiffness and strength compared to untreated fibers. Specifically, the tensile strength of treated fibers was enhanced by 100.4% compared to that of their untreated counterparts, corroborating the findings in [23]. This increase is attributed to the removal of surface impurities, such as wax, fat, lignin, and hemicellulose [24], which hindered load transfer within the fiber.

Similarly, the elastic modulus of treated fiber increased by 26.2% compared to untreated fibers. Comparable results were reported in [25,26], where a 41% increase in elastic modulus in fibers treated with a 5% NaOH solution was observed, compared to the 0.5% solution used in this study.

The stress-strain relationship of untreated and treated fibers is compared in Figure 7. The strain values were calculated as the stroke value obtained from the UTM, divided by the initial fiber length of 25 mm.

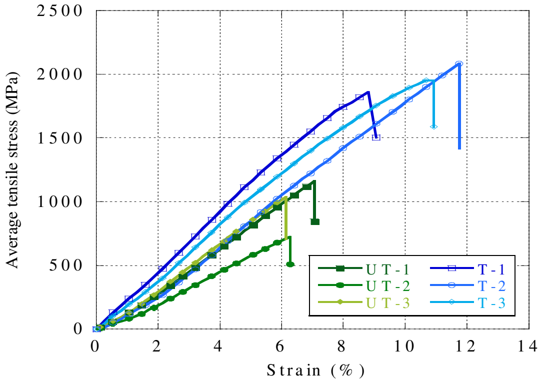

Fig. 7. Stress-strain relationship of single abaca fibers (treated and untreated).

It is observed that all fibers exhibit a linear response from the beginning of loading until the rupture point of fibers. The post-peak behavior is also the same, characterized by a sudden drop right after the peak load. This means that the alkali treatment does not substantially impact the stress-strain behavior at any loading stage.

C. *Tensile Test of AbFRP Laminates*

Table III summarizes the results of the tensile test of both untreated and treated AbFRP laminates.

TABLE III. MECHANICAL PROPERTIES OF ABFRP LAMINATES

Mechanical Properties	**Untreated**			**Treated**		
	UT-1	**UT-2**	**UT-3**	**T-1**	**T-2**	**T-3**
Thickness [mm]	1.6	1.8	1.7	1.6	1.6	1.7
Cross section, A [mm^2]	76.8	88.2	83.3	76.8	86.4	88.4
Tensile strength, f_s [MPa]	78.0	78.2	77.4	78.4	68.9	67.2
Strain at break [%]	1.7	1.6	1.6	5.3	5.7	5.1
Elastic modulus, E [GPa]	4.6	4.7	4.7	5.3	5.7	5.1

The effect of alkali treatment is obvious in the mechanical properties of AbFRP laminates. Laminates made from untreated fibers exhibited a tensile strength of 77.9 MPa, a strain at break of 1.6%, and an elastic modulus of 4.7 GPa. In contrast, laminates made from treated fibers manifested a tensile strength of 71.5 MPa, a strain at break of 1.3%, and an elastic modulus of 5.4 GPa. In greater detail, the tensile strength of treated laminates decreased by 8.2% compared to the/that of their untreated counterparts, contradicting the findings in [26], where a 7.8% increase in tensile strength was reported for similarly treated laminates. This discrepancy is likely due to differences in fabrication methods, as specialized molding techniques where deployed, whereas in this study manual fabrication was utilized resulting in non-uniform fiber tension. Consequently, fibers with higher tensile strength are preferentially stressed, leading to their premature failure and subsequent stress redistribution to weaker fibers. Regarding the elastic modulus, treated specimens exhibited a 14.9% increase in elastic modulus compared to the untreated specimens, which is in full agreement with the results in [23].

The comparison between the stress-strain relationship of untreated and treated fibers is presented in Figure 8. Both types of laminates exhibited linear behavior from the beginning of loading until rupture, similar to the behavior of synthetic fibers, such as CFRP and GFRP. Thus, it is essential to limit the stress value for sustainable structural applications. Design guidelines, including ACI440.2R-17, prescribe a safety factor for constraining the stress value employed in the design process. This approach minimizes the risk of sudden failure when these materials are utilized in structural applications.

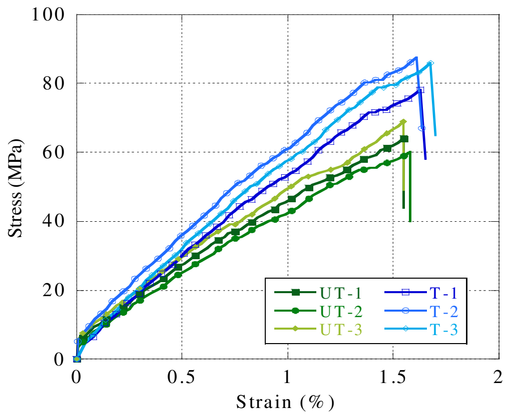

Fig. 8. Stress-strain relationship of AbFRP laminates (treated and untreated).

D. *SEM Results*

Figure 9 illustrates the SEM results of treated AbFRP laminates. Abaca fibers have a good adhesion with epoxy, while partial failure phenomena are evident; some fibers ruptured in particular regions, whereas others remained composite with epoxy.

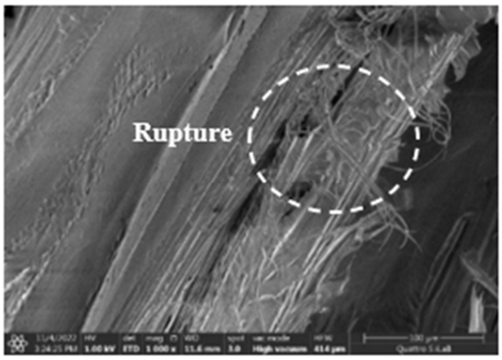

Fig. 9. Interaction between abaca fiber and epoxy.

E. *Failure Mode*

Figure 10 portrays the failure mode observed in both untreated and treated AbFRP laminates. All specimens exhibited a typical failure pattern, with fractures evidenced in the test area rather than in the grip area. According to ASTM D3039, the failure pattern depicted in Figure 10c corresponds to the Angled Gage Middle (AGM) type. The AGM failure mechanism typically initiates with a crack at a weak point in the material, such as a broken fiber end or a matrix defect. This crack then spreads to form a certain angle influenced by the fiber orientation, the mechanical properties of the matrix, and the applied stress level. As the crack continues to spread to a critical size, it leads to complete material failure.

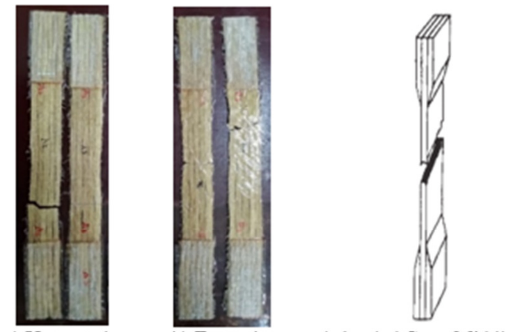

Fig. 10. Failure mode.

IV. CONCLUSIONS

The present study provides a comprehensive understanding of the properties of both abaca single fibers and Abaca Fiber Reinforced Polymer Laminates (AbFRP). Based on the experimental results, the following conclusions were drawn:

- The significant improvements in tensile strength, strain at break, and elastic modulus of single abaca fibers after alkali treatment, are noteworthy. This suggests that the treatment effectively removes impurities and enhances the structural integrity of fibers.
- Although alkali treatment slightly reduced the mechanical properties of AbFRP laminates, the overall performance remains impressive. This indicates that the treatment might present a trade-off between enhancing fiber properties and affecting the laminate's overall strength.
- The properties of single abaca fiber and AbFRP laminates are comparable to those of other natural fiber-reinforced polymers, such as those made from jute, hemp, and flex.
- AbFRP laminates demonstrate exceptional mechanical properties, making them promising candidates for sustainable structural application. This is a significant contribution considering the growing demand for eco-friendly construction materials.

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