Tensile Strength and Microstructure Analysis of Coconut Frond Fiber Composite Based On Polyester Resin With Fiber Orientation Variation

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Abstract.
The exploration of eco-friendly composite materials incorporating agricultural biomass waste has intensified to reduce reliance on synthetic components. This study evaluated the tensile mechanical behavior and micromorphological failure characteristics of coconut frond fiber-reinforced composites in a polyester matrix, using five fiber orientation angles (0, 30, 45, 60, and 90 degrees). Specimens were fabricated using the hand lay-up method and tested for tensile strength following ASTM D638, followed by microstructural failure characterization using Scanning Electron Microscopy (SEM) under ASTM E986. Results show that fiber orientation had a significant, non-linear effect on the mechanical response of the material. The lowest average tensile strength was found in the 30-degree specimens at 8.53 MPa, caused by dominant interlaminar shear stress at the fiber-matrix interface. In contrast, the best mechanical performance occurred at 60-degree orientation, reaching an ultimate tensile strength of 22.18 MPa, driven by effective mechanical interlocking between fibers and efficient load transfer. SEM observations confirmed that brittle fracture dominated the failure mode, accompanied by micro-voids, interfacial debonding, and fiber pull-out. These findings indicate that coconut frond fiber composites oriented at 60 degrees hold strong potential as a lightweight, environmentally friendly structural alternative to synthetic timber boards.

Keywords: *Composite; Coconut Frond Fiber; Fiber Orientation; Polyester Resin; SEM and Tensile Test*

I. INTRODUCTION

The development of material technology today is driving the use of eco-friendly alternative materials derived from abundant natural resources. One major focus is the use of natural fiber as reinforcement in composite materials to replace synthetic materials that are difficult to decompose and harmful to the environment. Natural-fiber-based composites offer advantages such as light weight, relatively low production cost, and easily obtainable raw materials. Indonesia, as an agrarian country, has substantial agricultural waste potential, one of which comes from coconut plants. According to the Central Statistics Agency (BPS), the utilization of coconut in Indonesia is mostly focused on the fruit, while the coconut frond remains underutilized and is generally treated as waste, even though it contains lignocellulosic fiber that has potential as a composite reinforcement.

Previous studies have examined the use of coconut fiber as composite reinforcement, reviewing the effect of fiber length and volume fraction on mechanical properties, but most studies on fiber orientation only compared three extreme angles, namely 0°, 45°, and 90°. This approach is able to show the general tendency that the highest tensile strength occurs at an orientation parallel to the load (0°) and the lowest at an orientation perpendicular to the load (90°), but it has not been able to describe in detail how the tensile strength decreases gradually between these three points. This research gap forms the basis for adding the 30° and 60° orientation points in the present study, in order to obtain a more comprehensive picture of the tensile strength trend of coconut frond fiber composites based on polyester resin.

Based on the above description, this study aims to analyze the tensile strength and microstructure of coconut frond fiber composite based on polyester resin with fiber orientation variations of 0°, 30°, 45°, 60°, and 90°. The results of this study are expected to provide scientific information on the characteristics of coconut-frond-based composite materials and serve as a basis for developing eco-friendly materials with higher use value as an alternative to wood or particle board in simple products such as interior panels, light tables, or furniture components.

II. LITERATURE REVIEW

Darmanto, Sediono, Setyoko, and Murni (2010) studied coconut frond as a composite fiber and found that it contains a fairly high lignocellulosic fiber content that has potential as a composite reinforcement, although the study was still limited to mechanical strength testing and did not address material quality as a whole. Setiawan, Azwar, and Nurhanisa (2020) examined the use of coconut frond as a filler in polypropylene-based wood-plastic composites and showed that coconut frond affects the physical and mechanical properties of the composite, although the study did not review the general quality of coconut-frond-based composites. Rahmawati and Hidayat (2020) reported that composite boards made from coconut frond have potential as a substitute for lightweight wood, but the study still focused on mechanical properties and did not comprehensively analyze material quality. These three studies confirm that coconut frond has potential as composite reinforcement, but none specifically examined the effect of fiber orientation variation in detail.

A composite material is composed of two or more different materials combined to produce mechanical and physical properties superior to those of the individual constituents. According to Callister and Rethwisch (2014), a composite consists of two main components, namely the matrix, which functions as a binder, and the reinforcement, which increases the strength and stiffness of the material. Coconut frond is part of the coconut plant that contains lignocellulosic fiber consisting of cellulose (40-55%), lignin (20-35%), and hemicellulose (15-25%), with a fiber density of 1.2-1.5 g/cm^3, and it is anisotropic, meaning it has maximum strength in the direction parallel to the fiber.

Fiber orientation is one of the key factors influencing the mechanical properties of composite materials because natural fiber is anisotropic. According to Hull and Clyne (1996), the strength and stiffness of a composite strongly depend on the fiber direction relative to the direction of the applied force. When the fiber is arranged parallel to the loading direction (0°), the tensile load is transferred directly to the fiber, producing high tensile strength. At a 45° orientation, the fiber receives a combination of tensile and shear stress at its maximum, so according to Mallick (2007) the composite strength at this angle generally lies between the 0° and 90° orientations. Conversely, at a 90° orientation (perpendicular to the load), the load is almost entirely borne by the matrix, resulting in the lowest tensile strength. The addition of the 30° and 60° orientation points in this study aims to map the gradual decrease and increase in tensile strength between the parallel and perpendicular conditions.

Polyester resin was chosen as the matrix because it is easy to process, has good adhesion to natural fibers, and cures relatively quickly with the aid of an MEKP catalyst (Jones, 1999; Gibson, 2012). Tensile strength testing of the composite refers to the ASTM D638 standard for polymer materials and fiber-reinforced composites, while the microstructure of the fracture surface was observed using a Scanning Electron Microscope (SEM) in accordance with ASTM E986 and ASTM E1508, used to identify phenomena such as fiber pull-out, debonding, matrix cracking, and voids at the fiber-matrix interface.

III. RESEARCH METHOD

This study is a laboratory experimental research aimed at analyzing the tensile strength and microstructure of coconut frond fiber composite based on polyester resin with fiber orientation variations of 0°, 30°, 45°, 60°, and 90° relative to the loading direction. The research process included material preparation, fabrication of composite plates using the hand lay-up method, curing, specimen cutting according to the testing standard, tensile testing, and microstructure observation using SEM.

The equipment used included a composite mold, digital scale, calipers, Scanning Electron Microscope (SEM), resin brush and roller, measuring cylinder, tensile testing machine (Universal Testing Machine), and personal protective equipment consisting of rubber gloves and a mask. The materials used included dried and cleaned coconut frond fiber, polyester resin as the matrix, MEKP catalyst (±1-2% of resin volume), release agent, and alcohol for cleaning the fiber.

Specimens were fabricated using the hand lay-up method. Cleaned and dried coconut frond fiber was cut to the mold length and arranged according to five orientation variations (0°, 30°, 45°, 60°, and 90°). Polyester resin was mixed with MEKP catalyst until homogeneous, then poured into the mold as the first layer. The arranged fiber was placed on top of the resin layer and coated again until fully impregnated, then flattened using a brush or roller to prevent void formation. The composite plate was cured at room temperature for approximately 24 hours, then cut into Type I tensile specimens according to ASTM D638.

The independent variable in this study was the fiber orientation of coconut frond (0°, 30°, 45°, 60°, and 90°). The dependent variables included maximum tensile strength (MPa), strain (%), elastic modulus (MPa), and microstructural characteristics (fracture pattern, fiber pull-out, matrix cracking, and voids). The control variables included fiber type, matrix type, catalyst percentage (±1-2%), fiber volume fraction, fabrication method (hand lay-up), curing time (±24 hours), specimen dimensions according to ASTM D638, and the loading rate of the tensile testing machine, all of which were kept constant so that differences in results were solely attributable to fiber orientation variation.

Tensile testing was carried out using a Universal Testing Machine (UTM) in accordance with ASTM D638. The specimen was mounted in the machine grips parallel to the loading direction, then loaded gradually until fracture occurred. The maximum tensile force (F) and elongation (ΔL) data were recorded to calculate stress, strain, and elastic modulus using the following equations:

$$\sigma = F / A$$

$$\varepsilon = \Delta L / L_0$$

$$E = \sigma / \varepsilon$$

where σ = tensile stress (MPa); F = maximum force (N); A = original cross-sectional area of the specimen (mm^2); ε = strain; ΔL = elongation (mm); L_0 = original gauge length (mm); E = tensile elastic modulus (MPa).

Microstructure observation was carried out using a Scanning Electron Microscope (SEM) on the fracture surface of the tensile-tested specimens, which had been cleaned of dust and loose particles. Observations focused on the interaction between fiber and matrix to identify fiber pull-out, debonding, matrix cracking, fiber distribution, and the presence of voids, in order to support the analysis of the tensile test results.

IV. RESULTS AND DISCUSSION

Tensile Strength of the Composite

Table 1. Average Tensile Strength of the Coconut Frond Fiber Composite

Fiber Orientation	Average Tensile Strength (MPa)	Average Yield Stress (MPa)	Average Strain (%)
0°	11.10	9.85	1.53
30°	8.53	7.80	0.83
45°	13.44	12.28	1.00
60°	22.18	20.57	0.90
90°	17.70	16.22	0.73

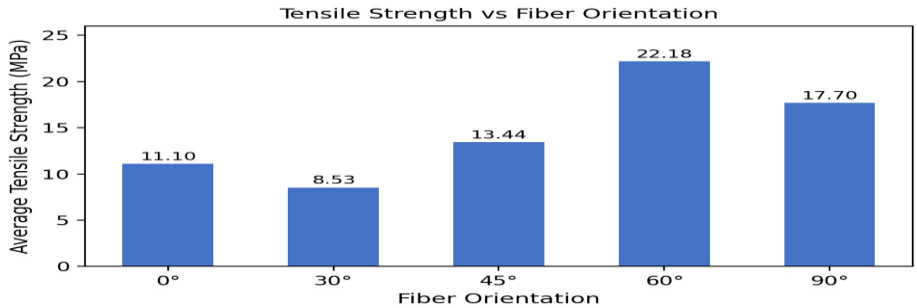

Fig. 1. Average Tensile Strength versus Fiber Orientation

Table 1 and Figure 1 show that the average tensile strength of the coconut frond fiber composite varied with the fiber orientation angle, ranging from 8.53 MPa to 22.18 MPa. At a 0° orientation, the composite withstood a tensile load of 11.10 MPa because the fiber direction was parallel to the direction of the tensile force, allowing the fiber to function effectively as the main load-bearing element. The tensile strength then decreased to 8.53 MPa at a 30° orientation, the lowest value in this study, caused by the dominance of interlaminar shear stress at the fiber-matrix interface, which triggered early failure in the form of matrix debonding.

An increase in tensile strength began to appear at the 45° orientation (13.44 MPa) and reached its optimum value at the 60° orientation (22.18 MPa). This increase indicates that the combination of load transfer mechanism and inter-fiber adhesion bonding was at its most efficient condition for resisting the axial tensile force, presumably due to a maximum mechanical interlocking effect from the natural morphology of the coconut frond fiber. However, at a 90° orientation, the tensile strength decreased again to 17.70 MPa because the fiber no longer acted as the main reinforcement in the direction of the force, but merely as a filler, so failure was dominated by matrix cracking without significant load resistance from the fiber.

All orientation variations exhibited linear deformation behavior in the early stage of loading, indicating the elastic region of the material, with the highest slope of the stress-strain curve shown by the 60° orientation, indicating the most optimal stiffness. After passing the maximum stress point, all specimens experienced a sudden stress drop, indicating brittle fracture typical of the polyester matrix.

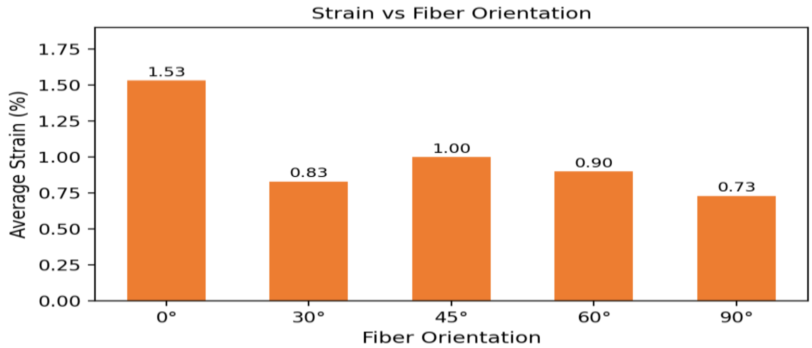

Fig. 2. Average Strain versus Fiber Orientation

Figure 2 shows that the highest average strain occurred at the 0-degree orientation (1.53%), reflecting the deformation capacity of fibers aligned with the load prior to fracture, while the lowest strain occurred at the 90-degree orientation (0.73%) because the material failed more quickly through brittle matrix cracking. This strain pattern does not fully align with the tensile strength pattern, particularly at the 60-degree orientation, which had the highest tensile strength but a relatively low strain (0.90%), indicating that the composite at this orientation is stiff and strong rather than ductile.

SEM Microstructure Results

SEM observation of the fracture surface showed that the failure mechanism was dominated by brittle fracture, characterized by relatively flat fracture surfaces (cleavage-like planes) accompanied by crack propagation grooves (river patterns) at high magnification (20.00 kX). At medium-to-low magnification (5.00 kX), interfacial debonding, fiber pull-out, and voids were observed in several areas, indicating that the adhesion bond between the coconut frond fiber and the polyester resin matrix was still not optimal. In addition, agglomeration of filler particles was identified, acting as stress concentration sites that triggered crack initiation in the material. These microstructural findings are consistent with the tensile test results, in which the suboptimal interfacial bonding also limited the overall tensile strength of the composite, particularly at the 30° and 90° orientations.

V. CONCLUSION AND SUGGESTION

The tensile strength of the coconut frond fiber composite based on polyester resin with fiber orientation variations of 0°, 30°, 45°, 60°, and 90° was shown to have a significant and non-linear effect, with average values ranging from 8.53 MPa to 22.18 MPa and strain ranging from 0.73% to 1.53%. The highest tensile strength was achieved at the 60° orientation due to an optimal mechanical interlocking mechanism between fibers, while the lowest tensile strength occurred at the 30° orientation due to the dominance of interlaminar shear stress that triggered matrix debonding. SEM observation of the microstructure showed that the material failure mechanism was dominated by brittle fracture accompanied by fiber pull-out, interfacial debonding, and the presence of voids, indicating that the adhesion bond between the coconut frond fiber and the polyester resin matrix was still not optimal. These findings demonstrate that coconut frond fiber composite, particularly at the 60° orientation, has the potential to be used as a lightweight structural material as an alternative to wood or particle board.

Future research is recommended to apply fiber surface treatment, such as alkali (NaOH) immersion, to improve the quality of the fiber-matrix interfacial bond and reduce the fiber pull-out and debonding phenomena. The number of test specimens for each orientation variation should also be increased to obtain more statistically representative data, given that a fairly wide scatter of values was still found at the 30° and 90° orientations. Physical property testing can be complemented with density and water absorption tests to make the material characterization more comprehensive, while further research is recommended to examine orientation variations around the 60° angle (e.g., 50°-70°) or hybrid/woven fiber configurations to further optimize the tensile strength of coconut frond composites.

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