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The Effect of Alkali Treatment Duration on the Tensile Strength and Physical Properties of Polyester Composites Reinforced with Coconut Fiber

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ABSTRACT

This study aims to determine the effect of alkali treatment duration with NaOH on the tensile strength and physical properties of coconut fiber-reinforced composites. The method used in this study was experimental, with variations in the duration of alkali treatment: 1, 2, and 3 hours. A total of 15 specimens were used for tensile testing. The specimens were prepared by hand lay-up, and tensile testing was conducted according to ASTM D638. The collected data were analyzed descriptively and presented in tables and graphs. The results of this study indicate that the duration of alkali treatment on fibers can affect the tensile strength and physical properties of polyester composites reinforced with coconut fiber. The results of this study show that the highest tensile strength was obtained at an alkali treatment duration of 1 hour, with a value of 19.322 MPa, and the lowest tensile strength was obtained at 2 hours, with a value of 13.826 MPa. The highest elastic modulus was observed at an alkali treatment duration of 3 hours with a value of 16.842 MPa. The lowest elastic modulus was observed at an alkali treatment duration of 1 hour with a value of 12.857 MPa. The microstructure photos were consistent with the tensile strength, i.e., the fewer defects in the fracture, the higher the tensile strength.

1. Introduction

Engineering materials are materials used in various engineering and manufacturing processes to fulfill specific mechanical, physical, chemical, and aesthetic functions. Engineering materials are very diverse, including metals, polymers, composites, and other advanced materials [1]. Composites consist of a matrix and fibers; they are multiphase material systems composed of two or more materials with different characteristics. Fiber composite materials have many advantages, such as easier, cheaper manufacturing processes and readily available raw materials [2]. There are two types of fibers used as composite reinforcements: natural and synthetic fibers. The following are the advantages of natural fibers: they are environmentally friendly, have no negative impact on health, are abundantly available, inexpensive, have low density, are economically sustainable, aesthetically pleasing, and have good mechanical properties [3]. In contrast, synthetic fibers can

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have an impact on the environment; for example, their waste is difficult to decompose, has a negative impact on health, and production costs are high [4].

Natural fibers have long been used to meet human needs in various industries, including textiles, paper, crafts, accessories, decorations, and biocomposite materials. Natural fibers produced in Indonesia include vegetable fibers such as cotton, hemp, coconut fiber, pineapple leaves, and bamboo, as well as animal fibers such as silk, wool, and collagen [5]. One of the abundant natural fibers in Indonesia is coconut fiber. The chemical composition of dry coconut fiber consists of 5.43% moisture content, 30.34% crude fiber, 3.95% ash content, 3.54% lignin, 0.52% cellulose, and 23.70% hemicellulose [6]. Coconut fiber can be used as a substitute for synthetic fibers due to its mechanical properties [7]. To improve the mechanical properties of the fiber, alkali treatment is required to remove impurities. Alkali treatment can use NaOH. NaOH is a basic chemical solution that is readily soluble in water, and alkali treatment with NaOH can reduce the lignin and hemicellulose in fibers. However, the treatment duration must be considered [8]. Alkali treatment using sodium hydroxide can improve the adhesion/bonding of fibers to the matrix [9].

The alkali treatment duration is the time during which fibers are treated to remove impurities, such as lignin and hemicellulose, contained in the fibers [10]. The duration of treatment affects the resulting mechanical values [11]. The longer the treatment duration, the greater the effect on the mechanical properties and diameter of coconut fiber [12]. The duration of alkali treatment also affects the physical properties of the resulting composite; the more defects found, the more brittle the composite will be [13].

2. Method

The methodology used in this study was the experimental method. The experimental method aimed to determine the effect of alkali treatment duration on the tensile strength and fracture results of polyester composites reinforced with coconut fiber [14]. There were three variants of alkali treatment duration, namely 1 hour, 2 hours, and 3 hours. There were 15 test specimens, each treated with alkali for a different duration. The volume fraction of coconut fiber to polyester was 30% coconut fiber and 70% polyester.

The alkali treatment durations of 1, 2, and 3 hours used NaOH. To determine the mechanical properties of the specimens, a tensile test was conducted using a Universal Testing Machine 4160 in accordance with ASTM D638. There were 5 test specimens per treatment, for a total of 15. The results were analyzed, and the final results were presented as a graph of mechanical values against treatment duration.

3. Results and Discussion

3.1. Results

3.1.1. Tensile strength

After treating coconut fiber with alkali for 1, 2, and 3 hours, tensile testing was conducted using a Universal Testing Machine 4160 in accordance with ASTM D638. The tensile test results obtained are presented in diagram form to compare the mechanical values of specimens with different treatments. The test results for coconut fiber composites treated with alkali for different durations showed varying tensile strengths. Figure 1 shows the average tensile strength values of coconut fiber composites that had been treated with different alkalis.

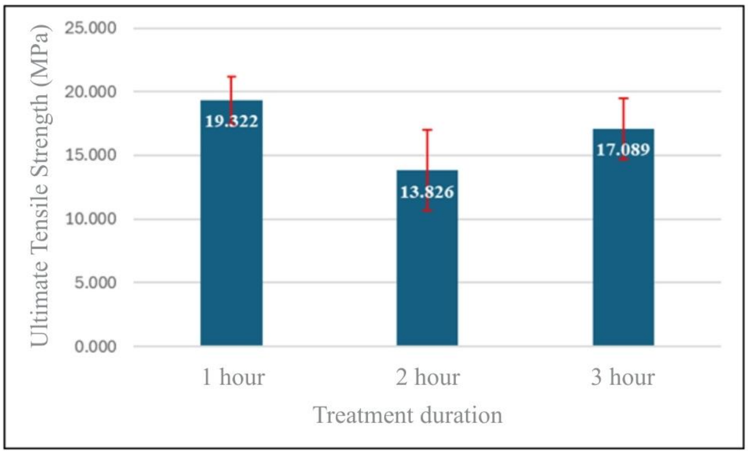

Fig. 1. Ultimate tensile strength of composites

From Figure 1, it can be seen that the highest tensile strength was obtained for coconut fiber treated with alkali for 1 hour, with a value of 19.322 MPa. Meanwhile, the lowest tensile strength was observed in alkali-treated coconut fiber (2 hours), with a value of 13.826 MPa.

Based on the tensile test results of the coconut fiber composite, different elastic modulus values were obtained for each treatment duration. Figure 2 shows a diagram of the average elasticity modulus values obtained during the test.

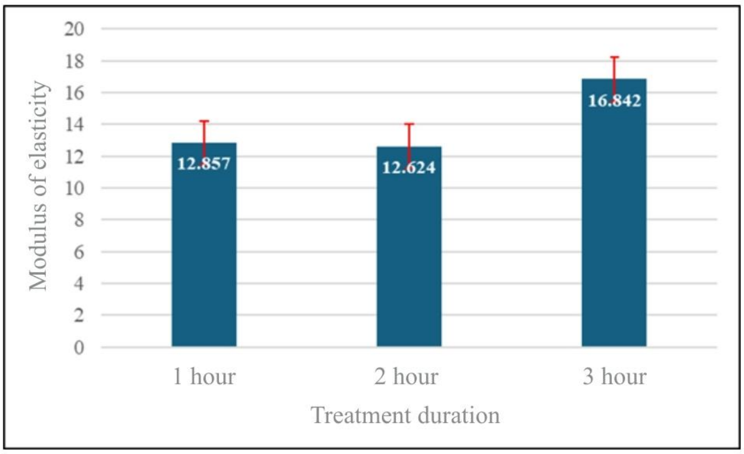

Fig. 2. Modulus of elasticity of composites

In Figure 2, the highest elastic modulus was observed in coconut fiber composites treated for 3 hours, with a value of 16.842 MPa. Meanwhile, the lowest elastic modulus was observed in alkali-treated composites after 2 hours, with a value of 12.624 MPa.

3.1.2. Microstructure

Microstructural photographs were taken to determine fracture patterns in tensile-tested coconut fiber composites. At 30x magnification, the defects found in the composites were clearly visible. In the study, the researchers found several defects in the composite fractures, such as voids, brittleness, and fiber pull-out. The following are the microstructure photos for each alkali treatment duration. After 1 hour of alkali treatment, several defects were found in the composite material, as shown in Figure 3.

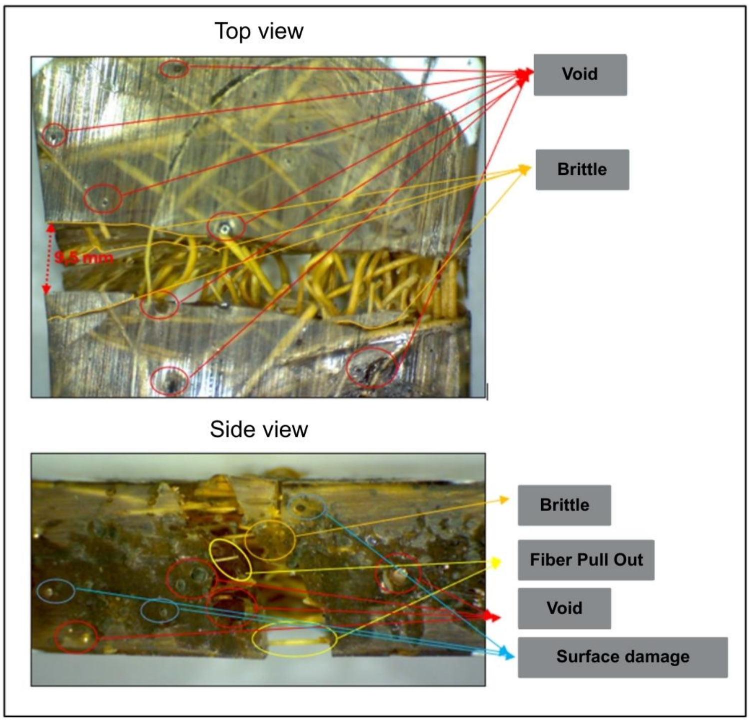

Fig. 3. Microstructure of 1-hour alkali treatment

Figure 3 shows defects in the form of voids, brittle fiber pull-out, and surface damage. Voids are caused by a suboptimal composite manufacturing process [15]. Fiber pull-out is caused by an insufficient bond between the fibers and the matrix [16]. At a treatment duration of 1 hour, the dominant indication was voids, which were caused by air trapped inside the mold.

The following is a composite specimen that was treated with alkali for 2 hours. The fracture results and indications found can be seen in Figure 4.

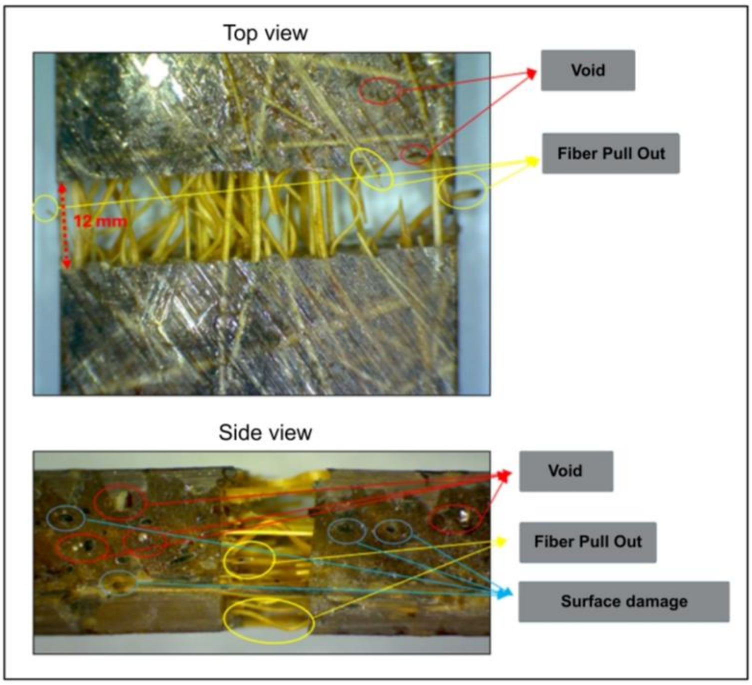

Fig. 4. Microstructure of 2-hour alkali treatment

Figure 4 shows defects found after taking microstructure photographs with 30x magnification. Defects in the form of voids and fiber pull-outs were found on the composite surface, but fiber pull-outs were more dominant. This was influenced by the duration of the treatment given [18]. The following are the results of microstructure photographs of composite material fractures resulting from tensile testing, as shown in Figure 5.

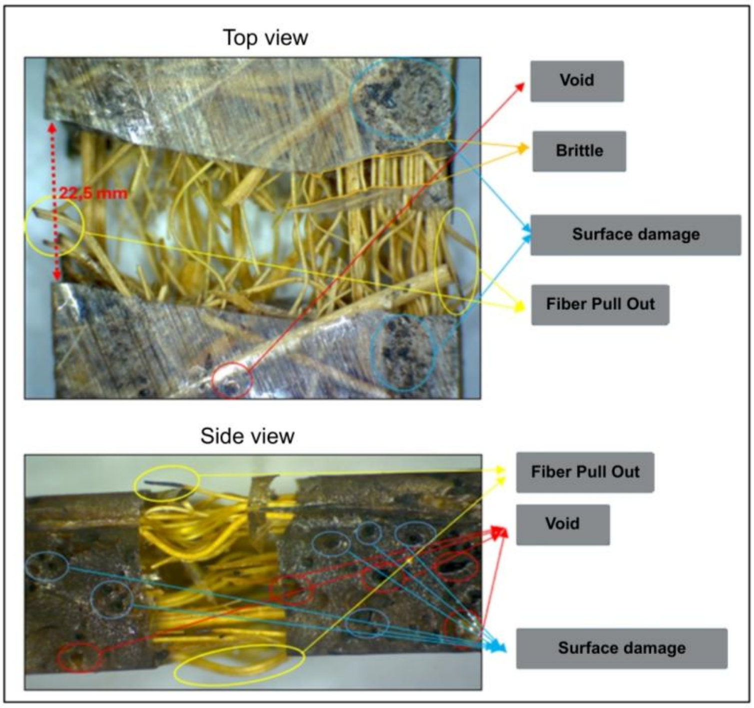

Fig. 5. Microstructure of 3-hour alkali treatment

As seen in Figure 5, indications of voids, fiber pull-out, and the onset of brittle fracture were found on the composite surface. Briettle occurs when parts of the material are not filled with fibers, so that, when loaded, only the polyester bears the load, causing cracks or breaks [19]. This is because the longer the treatment duration, the more it can alter the chemical structure of the fibers and their diameter [20].

Based on the results of the microstructure photos, there were several defects found in the impact test fracture results. The most dominant defect was fiber pull-out, caused by an inadequate bond between the coconut fiber and the polyester matrix. When comparing these microstructure photos with the tensile strength, a correlation emerged: the fewer defects observed in the fracture, the higher the tensile strength.

3.2. Discussion

The tensile response of the coconut fiber composites is clearly influenced by the duration of alkali treatment, indicating that treatment time alters the fiber surface condition and, consequently, the quality of stress transfer between the fiber and the matrix. Based on Figure 1, the composite treated for 1 hour achieved the highest ultimate tensile strength (UTS) of 19.322 MPa. At the same time, the 2-hour treatment produced the lowest UTS of 13.826 MPa. This non-monotonic trend suggests an optimal treatment window rather than a simple "longer is better" relationship.

A plausible interpretation is that 1-hour alkali treatment provides sufficient surface modification to enhance interfacial bonding—typically by partially removing surface impurities such as waxes, hemicellulose, and lignin—thereby increasing surface roughness and improving mechanical interlocking. Under this condition, the interface can transfer load more effectively from the matrix to the fiber, delaying debonding and fiber pull-out during tensile loading, resulting in a higher UTS.

In contrast, the reduction in tensile strength at 2 hours indicates that the composite's failure may have become dominated by premature interfacial damage or fiber degradation. Overexposure to alkali can lead to excessive removal of binding components and disruption of the cellulose microfibril structure, thereby reducing the fibers' intrinsic strength and weakening the interface.

Another practical possibility is that the 2-hour condition promoted unfavorable processing outcomes—such as increased fiber brittleness, poorer wetting, or higher void content—which would lower UTS by intensifying stress concentrations and accelerating crack initiation under tensile loading. Regardless of the exact mechanism, the 2-hour treatment appears to represent a condition where the net effect of alkali exposure is detrimental to tensile strength.

The modulus results in Figure 2 add an important nuance. The highest elastic modulus was obtained for the 3-hour treatment (16.842 MPa), while the 2-hour treatment again gave the lowest modulus (12.624 MPa). The increase in modulus at 3 hours suggests the composite became stiffer, likely due to increased fiber surface fibrillation, a higher effective fiber stiffness contribution, or improved restriction of matrix deformation. However, the fact that the 3-hour condition does not coincide with the highest UTS indicates a typical stiffness–strength trade-off seen in natural fiber composites: stiffness can increase while ultimate strength does not, especially if longer treatment increases brittleness, interfacial microcracking, or reduces the fiber's strain-to-failure. In other words, the 3-hour treatment may improve resistance to elastic deformation (higher modulus) but still allow earlier catastrophic failure (not maximizing UTS).

Microstructural observation of the tensile-fracture surfaces at 30× magnification provides direct evidence of the dominant failure mechanisms in coconut fiber–polyester composites. It helps explain the differences in tensile properties across alkali treatment durations. Across all specimens, three recurring defect features were identified—voids, fiber pull-out, and brittle fracture indications—each of which is known to reduce composite performance by degrading load transfer efficiency and accelerating crack initiation and propagation.

The 1-hour specimen shows voids, limited fiber pull-out, and some surface damage. The dominant feature reported is voiding, which is typically associated with entrapped air during lay-up/pressing and inadequate resin flow or consolidation. Voids act as stress concentrators under tensile loading, enabling microcracks to initiate earlier and coalesce into a macrocrack. Despite this, the relatively lower fiber pull-out dominance suggests that, at 1 hour, the fiber–matrix interface is more effective than in longer treatment cases. This microstructure is consistent with the tensile results, where the 1-hour treatment produced the highest tensile strength, indicating that the interface condition and fiber integrity may still be sufficiently preserved to promote better stress transfer, even though voids remain a processing-related limitation.

For the 2-hour specimen, the microstructure reveals voids, but, importantly, fiber pull-out becomes the most dominant defect. An extensive pull-out indicates that failure is primarily governed by interfacial debonding rather than fiber fracture. In practical terms, this means the applied tensile load is not effectively transferred from the polyester matrix to the coconut fibers; instead, the fibers detach and slide, consuming energy through friction but reducing the ultimate load capacity. This observation provides a strong mechanistic explanation for why the 2-hour treatment exhibited the lowest tensile strength and modulus in the previous section: the composite fails earlier because the interface is unable to sustain shear transfer, allowing cracks to propagate along the fiber–matrix boundary.

The dominance of pull-out at 2 hours also suggests that the treatment duration may have shifted the fiber surface condition away from an optimal state—either by failing to improve wettability/interlocking sufficiently or by causing changes that weaken interfacial adhesion. Regardless of the chemical pathway, the fracture morphology clearly points to interface-controlled failure as the governing mechanism for this condition.

The 3-hour specimen exhibits a mixed defect population: voids, fiber pull-out, and early signs of brittle fracture. The reported brittle behavior is associated with local regions of matrix-rich areas (insufficient fiber presence), where the polyester bears most of the load. Under tensile stress, these resin-dominated zones tend to crack more readily due to lower toughness and strain capacity relative to fiber-reinforced regions. Additionally, prolonged alkali exposure can modify fiber chemistry and geometry (including fiber diameter reduction), which can increase stiffness but also increase susceptibility to brittle response if fiber damage or reduced ductility occurs.

This morphology aligns well with the mechanical trend: the 3-hour treatment produced the highest modulus (stiffer composite), but not the highest tensile strength. A stiffer response can arise from increased rigidity of the reinforcing phase and reduced matrix mobility. However, ultimate strength remains limited if crack initiation is promoted by voids/matrix-rich zones and if the interface still permits pull-out.

4. Conclusions

This research evaluated the effect of alkali treatment duration (1, 2, and 3 hours) on the tensile behavior and fracture microstructure of coconut fiber–polyester composites. The results confirm that alkali treatment time significantly influences composite performance. The highest tensile strength was achieved with the 1-hour treatment (19.322 MPa). In contrast, the 2-hour treatment produced the lowest tensile strength (13.826 MPa), indicating that intermediate exposure can be detrimental to load-carrying capacity. In terms of stiffness, the elastic modulus peaked at 3 hours (16.842 MPa). It reached its minimum at 1 hour (12.857 MPa), showing that longer treatment can enhance rigidity even when it does not maximize ultimate strength. Microstructural observations support these trends: specimens with fewer fracture-surface defects exhibited better tensile performance, while the presence of voids, fiber pull-out, and brittle fracture features reflects suboptimal processing and interfacial bonding that reduce mechanical strength. Overall, the findings suggest an optimal alkali treatment window of approximately 1 hour to maximize tensile strength. In contrast, 3 hours is more favorable when higher stiffness is required, provided that defect formation and interfacial quality are controlled.

Conflict of interest

The authors declare no conflict of interest.

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