Effect of Sisal Fiber-Reinforced Composite Using Hand Lay-Up Method on Tensile Strength

Rizky Dian Rio Haryonoa), Moh. Jufrib), Suwarsonoc)and Muhammad Rafly Satriad)

Department of Mechanical Engineering, University of Muhammadiyah Malang   
Jl. Raya Tlogomas No. 246, Malang 65144, Indonesia.

a)rizkypkmn@gmail.com  
b)Corresponding author: jufri@umm.ac.id

c)suwarsono@umm.ac.id

d)35mrsatria@gmail.com

**Abstract.** Composite materials consist of two or more constituent materials with significantly different physical or chemical properties, which remain separate and distinct within the finished structure. In this study, sisal fibers (Agave sisalana) were used as natural reinforcement due to their availability and eco-friendly characteristics. A 5% NaOH alkalization treatment was applied to modify the fiber surface and improve interfacial bonding with the matrix. Composite specimens were fabricated using epoxy resin and volume fractions of 15%, 20%, and 25% via the hand lay-up method. Tensile tests were conducted to evaluate mechanical properties. The highest tensile strength without alkali treatment was 157.63 MPa at 20% fiber content. With 5% NaOH treatment, the tensile strength increased to 165.3 MPa at the same fiber fraction. The lowest tensile strength was found at 25% fiber content without treatment (109.6 MPa), while the treated fiber at 25% yielded 139.03 MPa. Fracture observations revealed fiber brittleness, voids, and fiber pull-out, indicating insufficient fiber-matrix bonding. This study highlights the potential of sisal fiber composites for structural applications with improved performance through alkalization treatment.

# INTRODUCTION

Composite materials have rapidly evolved and gained significant interest in recent years due to their ability to offer tailored mechanical properties suited for various engineering applications. Compared to metals, composites offer superior corrosion resistance and, in certain configurations, exhibit better strength and stiffness properties [1]. The increasing demand for lightweight and durable materials in the manufacturing industry has driven the development of advanced composites for structural and functional components. Innovations in material technology and mechanical engineering continue to emerge as a response to global challenges [2].

Composites possess several advantages including ease of material sourcing, corrosion resistance, design flexibility, extended service life, recyclability, durability, thermal insulation properties, and economic efficiency [3]. Among the many types of composites, fiber-reinforced composites are widely utilized due to their enhanced strength-to-weight ratio [4]. These composites consist of a matrix and reinforcing fiber, where the matrix serves as the binder while the fiber provides structural reinforcement [5].

Achieving optimal composite properties requires careful consideration of the matrix and filler phases, including type, size, volume fraction, and interfacial adhesion between the matrix and reinforcement [6]. In this study, epoxy resin was chosen as the matrix due to its superior mechanical strength, cost-effectiveness, excellent chemical resistance, impact tolerance, and strong adhesion properties compared to conventional thermosets or thermoplastics [7]. The use of natural fibers as reinforcement in composites has been extensively explored, and their potential to replace synthetic fibers has been widely acknowledged [8].

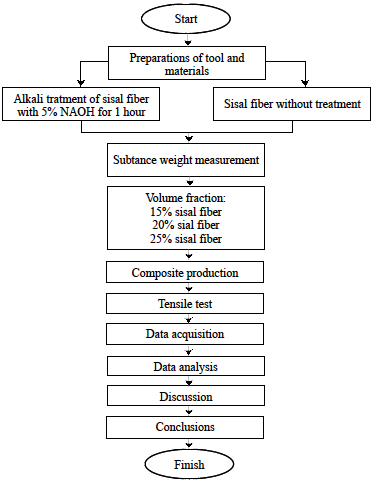
Sisal fiber (Agave sisalana) is one of the most commonly used natural fibers, known for its strength, availability, and suitability for cultivation in marginal lands. Globally, about 4.5 million tons of sisal fiber are produced annually, with Brazil and Tanzania as the leading producers, followed by Southeast Asian countries such as Indonesia and Thailand [9]. A single sisal plant produces approximately 200–250 leaves, with each leaf yielding 1,000–1,200 fiber bundles [10]. The physico-chemical and mechanical characteristics of sisal make it a suitable candidate for composite applications requiring both strength and flexibility [11]. Sisal fiber is composed of approximately 78% cellulose, 19% hemicellulose, and 8% lignin. High cellulose content contributes to the fiber’s strength and molecular crystallinity [12].

In this study, sisal fiber-reinforced epoxy composites were fabricated using both untreated and alkali-treated fibers. Alkalization was performed using a 5% sodium hydroxide (NaOH) solution to remove hemicellulose, lignin, and other amorphous components that negatively affect fiber-matrix bonding [13][14].

The hand lay-up method was employed for composite fabrication due to its simplicity and cost-effectiveness. The process involves pouring the resin onto the arranged fibers in layers, followed by rolling to ensure proper wetting and thickness control [15]. Despite its advantages, this method is prone to void formation due to air entrapment, which may degrade the mechanical integrity of the composite as a result of weak fiber-matrix interaction [16].

# Methodology

This study employed an experimental approach to evaluate the tensile strength of composite materials reinforced with sisal fiber (Agave sisalana). The research focused on the effect of fiber volume fraction and alkali treatment on mechanical performance. The experimental work was conducted at the Mechanical Engineering Laboratory of Universitas Muhammadiyah Malang, using locally prepared sisal fiber and standard composite fabrication techniques. Figure 1 illustrates the overall methodology used in this research.



**Figure 1.** Flowchart of composite fabrication and testing procedure.

Sisal fibers were first prepared by combing and cutting to uniform size, followed by two treatment conditions: untreated, and treated with 5% sodium hydroxide (NaOH) solution for one hour. This alkali treatment was intended to remove hemicellulose, lignin, and pectin, which interfere with the fiber–matrix bonding interface.

Epoxy resin was used as the matrix, and a compatible hardener was mixed to accelerate the curing process. Mirror glass was used as a mold base to prevent resin adhesion, and mold release wax was applied to ensure smooth demolding. Fiber volume fractions of 15%, 20%, and 25% were applied for both treated and untreated conditions. Each variation produced three replicate specimens, yielding a total of 18 specimens.

The composite specimens were fabricated using the hand lay-up method. The process began with applying release wax on the mold surface, followed by placing the sisal fiber into the mold according to the specified volume fraction. The epoxy resin and hardener were mixed at a manufacturer-recommended ratio, stirred until homogeneous, and gradually poured onto the fiber layer. A roller was used to compress the laminate and eliminate trapped air. The procedure was repeated in layers until the desired specimen thickness was reached. After curing at ambient conditions, the specimens were removed from the mold, trimmed, and shaped according to ASTM D638-03 tensile test standard.

The tensile tests were performed using a Shimadzu UH-300KNX universal testing machine with a maximum capacity of 300 kN.

# Results and Discussion

## Tensile Load of Composite Specimens

A total of 18 composite specimens were tested to evaluate the effect of sisal fiber volume fraction and NaOH alkali treatment on tensile performance. Each condition was tested with three replicate specimens. The experimental results show notable differences in maximum tensile load across fiber variations and treatment conditions.

Table 1 presents the tensile load data (in kN) for specimens without NaOH treatment. The highest average tensile load was observed at 20% fiber content, reaching 14.29 kN, while the lowest occurred at 15% with an average of 11.03 kN.

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| **TABLE 1.** Maximum tensile load of untreated specimens. | | | |
| **Fiber Volume Fraction** | **Specimen** | **Maximum Load (kN)** | **Average Load (kN)** |
| 15% | 1 | 8.917 | 11.027 |
|  | 2 | 12.800 |  |
|  | 3 | 11.364 |  |
| 20% | 1 | 13.628 | 14.293 |
|  | 2 | 14.045 |  |
|  | 3 | 15.207 |  |
| 25% | 1 | 12.334 | 12.911 |
|  | 2 | 14.066 |  |
|  | 3 | 12.333 |  |

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| **TABLE 2.** Maximum tensile load of specimens treated with 5% NaOH. | | | |
| **Volume Fraction** | **Specimen** | **Maximum Load (kN)** | **Average Load (kN)** |
| 15% | 1 | 6.995 | 7.163 |
|  | 2 | 8.099 |  |
|  | 3 | 6.393 |  |
| 20% | 1 | 10.737 | 9.975 |
|  | 2 | 8.481 |  |
|  | 3 | 10.707 |  |
| 25% | 1 | 8.929 | 9.343 |
|  | 2 | 9.159 |  |
|  | 3 | 9.940 |  |

Table 2 shows the corresponding data for specimens treated with 5% NaOH solution. A similar trend is observed, where the 20% fiber content yields the highest average tensile load at 9.97 kN, while the lowest is found at 15% with 7.16 kN.

## Tensile Strength Analysis

The tensile strength was calculated by dividing the maximum tensile load by the cross-sectional area of the specimen. Table 3 displays the tensile strength values (in MPa) for the untreated specimens. The highest tensile strength was recorded at 20% fiber content, reaching 157.63 MPa, while the lowest was at 25% with 109.6 MPa. The trend indicates an increase in strength from 15% to 20%, followed by a decrease at 25%.

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| **TABLE 3.** Tensile strength of untreated specimens. | | | |
| **Volume Fraction** | **Specimen** | **Tensile Strength (MPa)** | **Average (MPa)** |
| 15% | 1 | 111.3 | 135.7 |
|  | 2 | 161.4 |  |
|  | 3 | 134.4 |  |
| 20% | 1 | 149.5 | 157.6 |
|  | 2 | 152.0 |  |
|  | 3 | 171.4 |  |
| 25% | 1 | 108.9 | 109.6 |
|  | 2 | 111.0 |  |
|  | 3 | 108.9 |  |

As shown in Fig. 2, the tensile strength peaked at 20% fiber content. The subsequent reduction at 25% may be attributed to an excessive fiber ratio that inhibits proper matrix infiltration and bonding. Additionally, void formation due to trapped air may lead to reduced material density and mechanical performance.

**Figure 2.** Tensile strength of untreated specimens.

## Effect of Alkali Treatment on Tensile Strength

Table 4 summarizes the tensile strength values of specimens treated with 5% NaOH. Similar to untreated specimens, the maximum tensile strength was observed at 20% fiber volume, with an average value of 165.3 MPa, which represents an improvement over the untreated case. The 25% treated specimens showed an average strength of 139.0 MPa, and the 15% treated group reached 140.4 MPa.

Figure 3 illustrates the enhanced tensile performance after alkali treatment. The improved bonding is attributed to the removal of hemicellulose, lignin, and pectin, which increases fiber surface roughness and improves wetting by the epoxy matrix. This leads to better mechanical interlocking at the fiber–matrix interface.

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| **TABLE 3.** Tensile strength of untreated specimens. | | | |
| **Fiber Volume Fraction** | **Specimen** | **Tensile Strength (MPa)** | **Average (MPa)** |
| 15% | 1 | 132.0 | 140.4 |
|  | 2 | 156.9 |  |
|  | 3 | 132.3 |  |
| 20% | 1 | 178.6 | 165.3 |
|  | 2 | 142.3 |  |
|  | 3 | 174.1 |  |
| 25% | 1 | 131.1 | 139.0 |
|  | 2 | 138.1 |  |
|  | 3 | 147.9 |  |

**Figure 3.** Tensile strength of specimens treated with 5% NaOH.

## Failure Mode Observation

Fracture analysis revealed different failure modes depending on fiber content and treatment. In general, specimens showed signs of fiber pull-out, void formation, and brittle fracture. These phenomena are critical indicators of fiber–matrix interface quality.

Void formation was found to increase with higher fiber content, especially in the 25% group. Voids weaken the composite structure as they act as stress concentrators. They also disrupt load transfer between the fiber and matrix, leading to premature failure [17].

The dominant failure mode observed was fiber pull-out, particularly in untreated specimens. This indicates inadequate adhesion between fiber and matrix. Although the matrix and fibers may still possess sufficient strength, poor interfacial bonding results in early failure under tensile load [18][19][20].

Alkali-treated specimens demonstrated relatively less fiber pull-out and a more cohesive fracture surface, confirming the improved bonding achieved through surface modification. These findings suggest that alkali treatment enhances both mechanical strength and structural integrity of sisal-reinforced epoxy composites.

# CONCLUSION

This study examined the effect of sisal fiber volume fraction and 5% NaOH surface treatment on the tensile strength of epoxy-based composite materials. The results showed that the optimal fiber volume fraction was 20%, which provided the highest tensile strength in both untreated and treated conditions. In untreated composites, the maximum tensile strength reached 157.63 MPa, while in alkali-treated specimens, it increased to 165.30 MPa. The application of NaOH treatment significantly improved the interfacial bonding between the fiber and matrix by removing surface impurities such as hemicellulose and lignin, which in turn enhanced stress transfer and reduced fiber pull-out during fracture. Conversely, increasing the fiber content to 25% led to a decline in tensile performance, primarily due to inadequate resin penetration and the formation of voids, which weakened the fiber–matrix interaction. These findings suggest that composites with 20% sisal fiber treated with 5% NaOH offer the most favorable balance of strength and fiber distribution. Overall, this research confirms the potential of alkali-treated natural fiber composites as sustainable and mechanically reliable alternatives for structural and semi-structural applications.

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