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Impact of Sea Pandan Leaf Fiber Volume Fraction on the Tensile Strength and Structural Morphology of Polypropylene Composites

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ABSTRAK

Komposit polimer yang diperkuat serat alam semakin banyak dikembangkan karena harganya yang relatif terjangkau dan ramah lingkungan. Penelitian ini bertujuan untuk menganalisis kekuatan tarik dan morfologi komposit polipropilena yang diperkuat dengan serat daun pandan laut. Bahan penguat yang digunakan adalah serat daun pandan laut, sedangkan matriks yang digunakan berupa plastik polipropilena. Proses pembuatan komposit dilakukan dengan metode *compression molding* pada suhu 250°C selama satu jam. Variasi fraksi volume serat yang digunakan yaitu 20%, 25%, 30%, 35%, dan 40%. Hasil pengujian tarik menunjukkan kekuatan tarik tertinggi terdapat pada fraksi volume serat 35% sebesar 25,82 MPa, sedangkan kekuatan tarik terendah pada fraksi volume 20% sebesar 10,34 MPa. Berdasarkan hasil pengamatan SEM, ditemukan adanya rongga, retakan, serat yang terlepas, serta kotoran pada permukaan komposit.

Kata kunci: Komposit; Morfologi; Polipropilena; Serat; Uji Tarik

ABSTRACT

Natural fiber-reinforced polymer composites are increasingly developed due to their relatively low cost and environmental friendliness. This study aims to analyze the tensile strength and morphology of polypropylene composites reinforced with sea pandan leaf fibers. The reinforcing material used was sea pandan leaf fiber, while the matrix consisted of polypropylene plastic. The composite fabrication process employed the compression molding method at a temperature of 250°C for one hour. The fiber volume fractions used in this study were 20%, 25%, 30%, 35%, and 40%. The tensile test results indicated that the highest tensile strength, 25.82 MPa, occurred at a 35% fiber volume fraction, while the lowest strength, 10.34 MPa, was found at a 20% fraction. SEM observations revealed the presence of voids, cracks, fiber pull-outs, and impurities on the composite surface.

Keywords: *Composite; Fiber; Morphology; Polypropylene; Tensile Test*

1. INTRODUCTION

Polymeric composites reinforced with biological fibers are advanced materials consisting of polymers that function as binding matrices and natural fibers that serve as reinforcing agens [1], [2], [3]. The synergistic integration of these two components results in lightweight, durable, and environmentally compatible materials that have gained increasing significance across various industrial applications. The transition from synthetic to natural fiber reinforcement represents a paradigm shift in materials science, emphasizing sustainability, biodegradability, and the utilization of renewable resources [4], [5]. These composites are extensively employed in multiple sectors, particularly within the automotive industry, where weight reduction and mechanical performance optimization are of paramount importance.

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The automotive sector has undergone substantial advancements in the application of fiber-reinforced polymer composites, particularly for interior components such as instrument panels, door trims, and insulation structures [6]. Glass fibers, which have traditionally dominated this market, are progressively being replaced by bio-based fibers due to their lower production costs, reduced energy requirements during processing, and environmental benefits. Natural fibers exhibit desirable properties such as low density, high specific strength, and renewability, making them an appealing alternative to glass fibers for the next generation of sustainable automotive materials [7].

Natural fibers, including kenaf, jute, sisal, and banana, have been extensively investigated as polymer reinforcements because of their mechanical efficiency and ecological advantages [8], [9]. Among these, the screw pine or beach pandanus (*Pandanus tectorius*) has emerged as a promising yet underutilized natural resource that thrives abundantly along the coastal regions of South and East Asia, extending to Polynesia [10]. This plant serves a crucial environmental role in preventing soil erosion and functioning as a natural wind barrier. Traditionally, its leaves have been employed in the crafting of mats, hats, and decorative items. Nevertheless, its potential as a reinforcing material in polymer composites remains insufficiently explored despite its favorable fibrous structure and widespread availability.

The mechanical performance of fiber-reinforced composites largely depends on the interfacial adhesion between the fibers and the polymer matrix, as well as the fibers' capacity to efficiently transfer loads within the composite structure. A major challenge associated with natural fibers arises from their hydrophilic nature, which restricts interfacial compatibility with hydrophobic polymer matrices. This incompatibility leads to moisture absorption and dimensional instability, resulting in crack initiation and deterioration of mechanical properties[11], [12], [13]. Previous studies have implemented various chemical treatments, including alkaline and silane processes, to enhance fiber–matrix adhesion and improve the overall mechanical performance of the composites.

Polymeric materials serve as highly effective matrices in composite structures due to their processability, low density, and versatility in mechanical performance. Among thermoplastic polymers, polypropylene stands out as one of the most extensively utilized matrices in fiber-reinforced composites because of its high melting point, cost-effectiveness, and excellent thermal and chemical stability [14], [15], [16]. Polypropylene-based composites are particularly suitable for structural and automotive applications where lightweight and durability constitute critical design parameters. The ability of polypropylene to maintain mechanical integrity under thermal stress also substantiates its suitability for compression molding and other high-temperature forming processes.

In recent years, research on eco-friendly composite materials has intensified in response to growing concerns regarding environmental degradation and the need for renewable alternatives. Studies on polymer composites reinforced with bio-based fibers have opened promising pathways for reducing carbon emissions and valorizing waste resources. Marine pandan fibers, being both abundant and renewable, exhibit significant potential as reinforcing agents in polymer matrices, yet their mechanical performance remains insufficiently explored. Investigating their behavior within polypropylene matrices could provide valuable insights for advancing the development of sustainable engineering materials [17].

The effectiveness of a composite material depends not only on the intrinsic mechanical properties of the fiber and matrix but also on the fiber volume fraction and its distribution within the polymeric phase. Understanding how variations in fiber volume fraction influence tensile strength and fracture morphology provides a scientific basis for optimizing composite design. The incorporation of marine pandan fiber into polypropylene composites represents a significant step toward developing environmentally responsible, regionally sourced materials that are suitable for lightweight applications, particularly in the automotive and household product sectors [7], [18].

This study aims to evaluate the effect of marine pandan (Pandanus tectorius) fiber volume fraction on the tensile strength and morphological characteristics of polypropylene composites. The findings are expected to enhance understanding of bio-based fiber reinforcement mechanisms and contribute to advancements in natural fiber composite technology. The results may serve as scientific evidence supporting the replacement of synthetic fibers with sustainable natural alternatives, thereby fostering material innovation and promoting ecological sustainability within industrial applications.

2. MATERIALS AND METHOD

2.1 Material

The materials used in this research consisted of polypropylene (PP) as the polymer matrix and sea pandanus (*Pandanus tectorius*) fibers as the reinforcing material. Polypropylene was selected because it is a thermoplastic polymer with low density (0.90 g/cm³), high melting temperature (200–280°C), excellent moldability, and chemical resistance [19]. The polymer used in this study was supplied in the form of granules suitable for compression molding.

Sea pandanus fibers were obtained from coastal regions of Gunungkidul, Yogyakarta, Indonesia. The raw leaves were cleaned and cut into small strips before fiber extraction. The extracted fibers were treated using 6% sodium hydroxide (NaOH) solution at 100°C for one hour to remove lignin and hemicellulose, followed by thorough washing with distilled water until neutral pH was achieved. Afterward, the fibers were oven-dried at 60°C for three hours to ensure uniform dryness prior to mixing.

Figure 1. Raw and Alkali-Trated Sea Pandanus Fibers Used as Composite Reinforcement

2.2 Composite Fabrication

The composite specimens were produced through a compression molding technique. Initially, polypropylene and sea pandanus fibers were accurately weighed and blended according to the predetermined fiber volume fractions of 20%, 25%, 30%, 35%, and 40%. The fabrication employed a steel mold with internal dimensions of 200 mm × 105 mm × 5 mm, which was pre-coated with a thin layer of wax to minimize adhesion during the molding process. Polypropylene sheets served as the top and bottom layers, while the fiber–polymer mixture was positioned between them. The molding process was conducted at a temperature of 250°C for 60 minutes within an electric oven, ensuring uniform heat distribution and optimal impregnation of the matrix into the fibers. Upon completion of the heating stage, the mold was allowed to cool naturally at ambient temperature for one hour prior to demolding. The molded composite plates were subsequently trimmed and conditioned for subsequent mechanical characterization.

Table 1. Mass of Fiber and Matrix For Each Fiber Volume Fraction

Fiber Volume Fraction (%)	Fiber Mass (g)	Matrix Mass (g)
25	25.2	70.86
30	30.24	66.15
35	35.28	61.43
40	40.32	56.7

The calculation of fiber and matrix volumes was performed using the following equations:

a. Composite Volume Calculation (Vc)

Mold volume = composite volume ($V_{Cet} = V_C$)**;** So the composite volume:

$$V_c = p\ x\ l\ x\ t \tag{1}$$

b. Composition for Fiber and Polypropylene (PP)

Pandanus leaf fiber volume 20%

$$V_f = v_f + V_c \tag{2}$$

Pandanus leaf fiber mass

$$W_f = V_f + \rho_f \tag{3}$$

Matrix Volume

$$V_m = V_c + V_f \tag{4}$$

Matrix mass

$$W_m = V_m + \rho_m \tag{5}$$

where V_c is the composite volume, V_f and V_m are the fiber and matrix volume fractions, W_f and W_m are the masses of fiber and matrix, and ρ_f and ρ_m are their respective densities

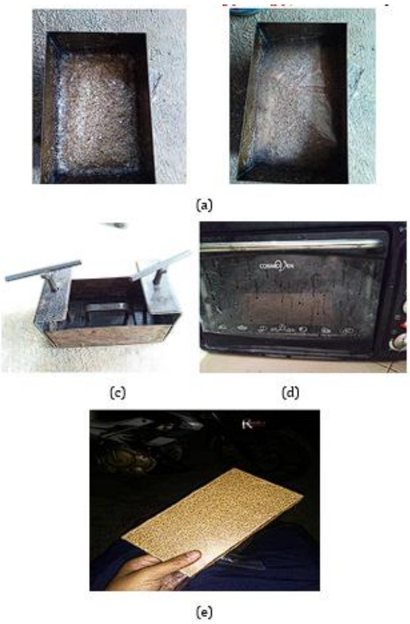

Figure 2. Fabrication stages: (a) fiber preparation, (b) fiber and polymer mixture in the mold, (c) compression molding at 250°C, (d) composite sheet after demolding

2.3 Specimen Preparation

Following the fabrication process, the composite sheets were precisely sectioned into tensile test specimens in accordance with the ASTM D638 Type I standard. The specimens were machined to a maximum thickness of 7 mm utilizing a high-precision cutting instrument to maintain dimensional accuracy. Five specimens were prepared for each variation in fiber volume fraction to guarantee measurement consistency and ensure statistical reliability of the experimental results.

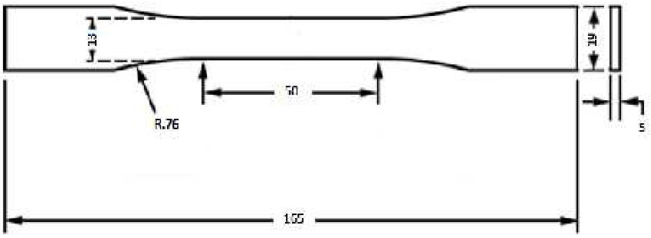

Figure 3. Dimensions of ASTM D638 Type I Tensile Specimen

2.4 Tensile Testing

Tensile tests were conducted using a Zwick Roell Z020 Universal Testing Machine at the Balai Besar Kulit, Karet, dan Plastik (BBKKP) Yogyakarta. The crosshead speed was set at 5 mm/min. Tensile strength (σ) and strain (ε) were determined using the following equations:

$$\sigma = \frac{F}{A} \tag{6}$$

$$\varepsilon = \frac{\Delta L}{L_0} \tag{7}$$

where F is the applied load (N), A is the initial cross-sectional area (mm²), ΔL is the elongation (mm), and L_0 is the original gauge length (mm). The results obtained from the tensile tests were used to determine the maximum tensile strength and fracture characteristics at each fiber volume fraction.

Figure 4. Zwick Roell Z020 Tensile Testing Setup

2.5 Morphological Analysis

The fracture surface morphology was examined using Scanning Electron Microscopy (SEM) to investigate the interfacial bonding between the fiber and the matrix, the fiber pull-out behavior, and the formation of voids. The analysis was conducted with a Phenom G2 Pro SEM at magnifications of 200× and 500× at Brawijaya University, Malang. The SEM evaluation focused on specimens exhibiting the highest tensile strength (35% fiber fraction) and the lowest tensile strength (20% fiber fraction) to elucidate the correlation between fiber volume fraction and fracture mechanisms.

3. RESULTS AND DISCUSSION

3.1 Tensile Test Results

Tensilization testing of composite specimens reinforced with pandan leaf fiber using a polypropylene plastic matrix.

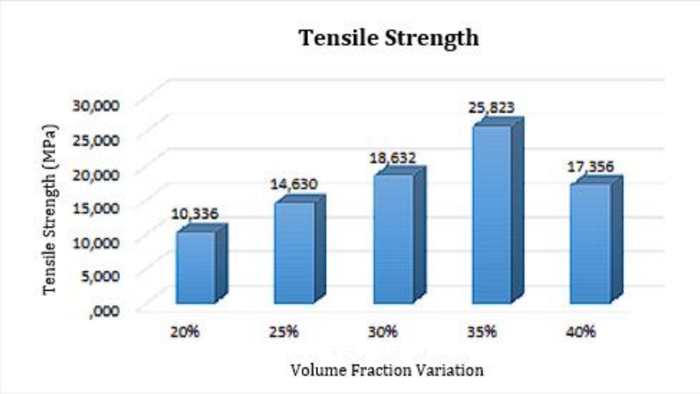

Figure 5. Graph of Average Tensile Strength of Polypropylene Composites

The tensile performance of polypropylene composites reinforced with sea pandan leaf fibers at varying fiber volume fractions (20%, 25%, 30%, 35%, and 40%) is illustrated in Figure 5. The corresponding average tensile strength values were recorded as 10.34 MPa, 14.63 MPa, 18.63 MPa, 25.82 MPa, and 17.36 MPa, respectively. Increasing the fiber volume fraction generally enhanced the tensile strength of the composites, corroborating the observations of Huo et al. (2023), Rahman et al. (2021), and Yang et al. (2022), who reported that greater fiber reinforcement promotes superior mechanical performance[20], [21], [22]. The maximum tensile strength was achieved at a 35% fiber fraction, reaching 25.82 MPa, whereas the lowest value was observed at 20%, with 10.34 MPa. The improvement at the optimal composition is attributed to the uniform dispersion of sea pandan fibers within the polymer matrix and the balanced matrix-to-fiber ratio, resulting in efficient stress transfer and reduced void formation throughout the composite structure [23].

The peak mechanical behavior observed at 35% fiber content suggests that appropriate fiber distribution and strong interfacial adhesion between the fiber and matrix are critical in enhancing tensile strength. A decline in strength at 40% fiber loading occurs due to an imbalance between fiber and matrix proportions, where insufficient matrix volume compromises the bonding capability, inducing fiber pull-out and micro-void generation that deteriorates structural integrity. These observations are consistent with the findings of Alo et al. (2022) and Baechle-Clayton et al. (2022), who emphasized that fabrication constraints and process variability may lead to internal imperfections, including voids, delamination, and uneven matrix distribution, ultimately reducing composite strength [24], [25]. Moreover, manual extraction of sea pandan fibers, as noted by Diyana et al. (2021), can inflict surface damage on the fibers, further diminishing their reinforcing effectiveness [26]. Despite the observed improvements, the tensile strength of the polypropylene–sea pandan fiber composite remains inferior to that of conventional polymers such as Acrylonitrile Butadiene Styrene (ABS), which typically exhibits a tensile strength of approximately 45 MPa [27]. This limitation indicates that the developed composite is not yet suitable for high-strength applications, including automotive dashboard components.

3.2 Scanning Electron Microscope (SEM) Test Results

Scanning Electron Microscope (SEM) examination was conducted on tensile specimens, revealing that the composite achieved its highest tensile strength at a 35% fiber volume fraction and its lowest at a 20% fraction. The SEM analysis employed magnifications of 200× and 500×.

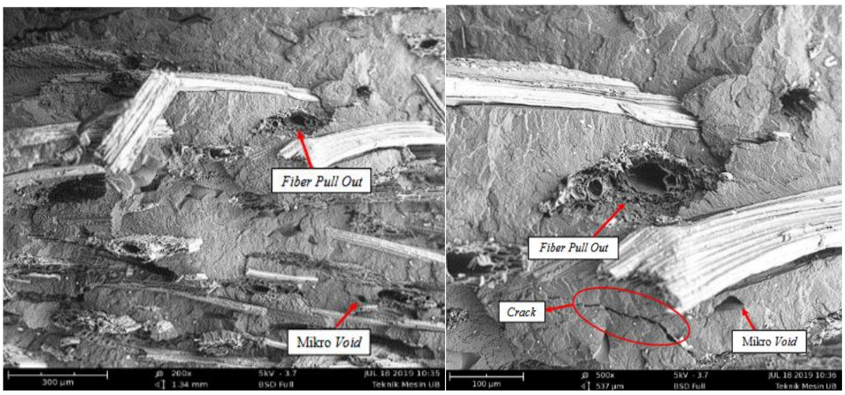

Figure 6. Fracture Morphology of Polypropylene Composite with 35% Fiber Volume Fraction

The SEM micrographs of the polypropylene composite containing a 35% fiber volume fraction demonstrated the presence of fiber pull-out phenomena, signifying interfacial failure between the polymer matrix and reinforcing fibers under tensile stress. During the tensile loading process, both the fibers and matrix bore the applied load; nevertheless, inadequate interfacial bonding resulted in debonding prior to the fracture of either phase. Although a limited number of micro-voids were detected, their sparse distribution allowed the composite to retain a relatively high tensile strength due to the uniform dispersion of fibers within the polypropylene matrix [28], [29]. The microscopic observations confirmed that the matrix adhered effectively to the pandanus leaf fibers, implying that an optimal fiber fraction enhances fiber–matrix interfacial bonding, facilitates efficient stress transfer, and promotes uniform stress distribution throughout the material. The primary failure mechanism was initiated by matrix cracking, followed by the propagation and coalescence of cracks that culminated in ultimate fracture. These cracks originated from micro-voids and interfacial discontinuities, which served as localized stress concentration sites during tensile deformation, contributing to a gradual decline in the specimen's tensile strength.

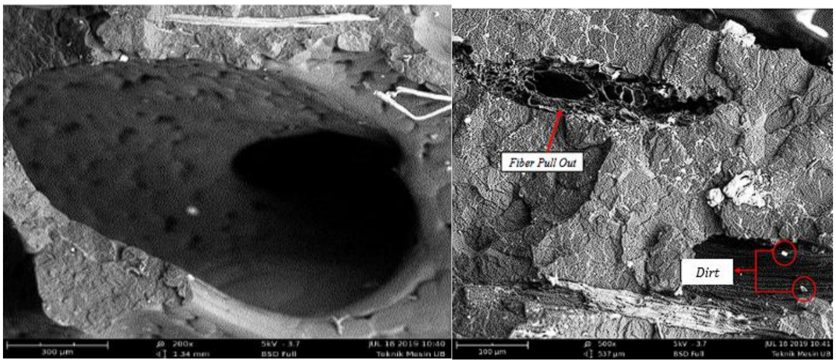

Figure 7. Fracture Morphology of Polypropylene Composite with 20% Fiber Volume Fraction

SEM observations presented in Figure 7 indicated that the polypropylene composite with a 20% fiber volume fraction contained numerous large air voids, primarily resulting from the non-uniform dispersion of fibers within the polymer matrix. The heterogeneous distribution of reinforcement created regions with fiber clustering and other areas lacking fiber presence, producing incomplete matrix infiltration. These structural inconsistencies weakened the interfacial bonding between fiber and matrix, as the tensile load tended to concentrate around void regions, leading to a reduction in the overall mechanical integrity of the composite [30], [31], [32]. The SEM images further revealed evident fiber pull-out, signifying poor interfacial adhesion between the fiber and matrix. This detachment mechanism during tensile deformation directly contributed to the reduced tensile strength observed at the 20% fiber fraction. Additionally, the presence of surface impurities on the fibers hindered the formation of robust interfacial bonds, intensifying the fiber pull-out phenomenon and diminishing the overall tensile performance of the composite material.

4. CONCLUSION

The experimental outcomes demonstrated that incorporating sea pandanus (*Pandanus tectorius*) fibers markedly improved the mechanical behavior of polypropylene composites, achieving an optimal tensile strength of 19.88 MPa at a 35% fiber volume fraction, an enhancement of approximately 63.72% compared with the unreinforced polypropylene matrix. This notable improvement resulted from alkali treatment of the fibers using a 6% NaOH solution, which effectively eliminated surface impurities, increased surface roughness, and strengthened the interfacial adhesion between fiber and matrix. Such modifications facilitated efficient stress transfer and stronger bonding under tensile loading conditions. Morphological examination through SEM substantiated these findings, indicating that composites with 35% fiber content exhibited compact fracture surfaces with minimal voids and well-integrated fibers, whereas lower fiber fractions displayed pull-out phenomena and inadequate adhesion, signifying weaker interfacial bonding. The reduction in tensile strength observed at a 40% fiber fraction was attributed to fiber agglomeration and insufficient polymer matrix coverage, resulting in void formation and premature crack initiation. Collectively, these findings underscore the promising potential of sea pandanus fibers as sustainable reinforcement materials for polymer composites, offering advantageous mechanical properties, low density, and biodegradability suitable for lightweight engineering applications such as automotive interior components and environmentally friendly structural materials. Continued refinement of fiber surface treatments and hybrid reinforcement techniques is recommended to further enhance durability and ensure performance reliability in industrial-scale applications.

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