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Bending Strength Analysis of Composite Materials with Coconut Fiber Reinforcement Using Manual Hand Lay-Up Method

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Abstract

This study investigates the mechanical performance of coconut coir fiber-reinforced composites with volume fractions of 30% and 40%, fabricated using the Manual Hand Lay-Up method. Specimens were tested under three-point bending following ASTM D790-03 to evaluate flexural strength. Results show that composites with a 30% fiber volume exhibit superior bending strength and stiffness compared to those with 40%, indicating a more optimal fiber–matrix ratio. The reduction in performance at higher fiber content is attributed to uneven resin distribution and inadequate fiber impregnation. These findings highlight the potential of coconut coir as a sustainable reinforcement material and emphasize the importance of optimizing fiber volume and manufacturing methods. The study recommends the use of alternative fabrication techniques, such as vacuum infusion, to improve resin homogeneity and mechanical reliability, particularly for structural and lightweight composite applications.

Keywords
Natural Fiber, Composite, Coconut Coir, Flexural Strength, Hand Lay-Up

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INTRODUCTION

The growing necessity for vehicle body materials characterized by lightweight properties, strength, cost-effectiveness, and environmental sustainability has catalyzed considerable innovation in the automotive sector. In the early 20th century, vehicle bodies were constructed utilizing wooden frames that were covered with thin metal sheets. Although these structures exhibited a high degree of robustness, they contributed significantly to the overall weight, thereby diminishing vehicle efficiency. Subsequent technological advancements have led to the incorporation of metals, including iron and aluminum; nonetheless, metal components still represent 25–30% of a vehicle's overall weight, resulting in a 7–10% reduction in fuel efficiency [1]. The search for alternative materials has been intensified, particularly focusing on composites, which present promising solutions for the construction of automotive bodies.

Composites are defined as materials that consist of two or more distinct constituents, generally comprising a matrix and a reinforcement phase. Each component within the composite maintains its unique physical and chemical properties [2][3]. The incorporation of these materials seeks to leverage their synergistic benefits—such as improved strength, stiffness, and corrosion resistance—rendering composites a progressively favored choice in structural applications [4]. Historically, synthetic fibers such as carbon fiber and glass fiber have been the predominant materials used for composite reinforcement within the automotive industry. Notwithstanding their enhanced mechanical properties, these materials present environmental challenges and are associated with significant costs, with production prices varying from IDR 1.2 to 2 million per square meter in prepreg form [5]. This situation is especially concerning in Indonesia, where 70% of automotive body components continue to be imported, leading to an annual trade deficit estimated at approximately USD 4.2 billion [5]. As a result, there is an increasing motivation to utilize natural fibers as a substitute reinforcement material.

Natural fibers, as shown in Figure 1—derived from plant, animal, or mineral sources—offer several advantages including low density, biodegradability, non-toxicity, high specific strength, and cost efficiency [6][7]. Examples include cotton, jute, silk, flax, and coir (coconut) fibers [8]. Among these, coir fiber has emerged as a particularly promising candidate due to its wide availability, low cost, and relatively strong mechanical performance [9]. Research indicates that coir fiber composites can significantly improve tensile and flexural properties, with tensile strength values ranging from 120–180 MPa—approaching those of glass fiber (200–300 MPa)—but at only 10% of the cost [10].

Figure 1. Coconut Coir Fiber

The fabrication method chosen in the composite manufacturing process plays a crucial role in determining the final product's characteristics, especially regarding the homogeneity of resin distribution, the extent of resin penetration into the fiber, and the resultant mechanical properties. The methods that are frequently utilized encompass vacuum infusion and manual hand lay-up techniques [11]. Cost-effectiveness emerges as a critical factor, particularly within the realms of experimental or small-scale research contexts. The benefits and constraints associated with each method are presented in Table 1.

Table 1. Comparison of Composite Manufacturing Methods [3]

Aspect	Vacuum Infusion	Manual Hand Lay-Up
Ease of Process	More complex: specialized equipment (e.g., vacuum pumps); less practical for small-scale research.	Simple and easy to implement; no specialized equipment required, ideal for small-scale studies.
Production Cost	Higher due to the need for pumps and additional tooling.	Significantly lower; minimal equipment required, making it highly cost-effective.

The manual hand lay-up method is one of the most widely used and simplest composite manufacturing techniques. It involves the application of liquid resin onto a mold surface, followed by the placement of reinforcing fibers. Each layer is manually saturated and leveled using a brush or resin roller, with the process repeated until the desired specimen thickness is achieved [12]. Given its practicality and low-cost advantages, particularly in resource-limited or educational settings, this study employed the manual hand lay-up method. As indicated in Table 1, this technique is well-suited for small-scale composite development and allows for adequate fiber-resin interaction without the need for specialized equipment.

METHOD

This research utilized a true experimental methodology characterized by a Completely Randomized Design (CRD). The specimens were produced utilizing the manual hand lay-up technique [13], incorporating two distinct variations of coir Fiber volume fractions: 30% and 40%. The principal reinforcement material employed in this study was coconut coir Fiber, whereas clear epoxy resin functioned as the matrix. All composite specimens were meticulously prepared and sectioned in accordance with the ASTM D790-03 standard for flexural testing, maintaining dimensions of 127 mm in length and 13 mm in width. The material specifications are summarized in Table 2.

Table 2. Research Object Specifications

Specification	Details
Type of Natural Fiber	Coconut Coir Fiber
Resin Type	Epoxy
Fiber Volume Fractions	30% and 40%
Composite Specimen Dimensions	As per ASTM D790-03 Standard
Specimen Width	13 mm
Specimen Length	127 mm
Support Span (L)	35 mm

This study aims to compare the flexural strength performance of composites with 30% and 40% volume fractions of coconut coir Fiber, which were fabricated utilizing the manual hand lay-up method. The present study aims to investigate the influence of this fabrication method on the uniformity of resin distribution and the overall mechanical properties, with a particular focus on the bending strength characteristics of the material.

The three-point bending test was employed to assess essential mechanical properties, encompassing flexural strength, modulus of elasticity, and specimen deflection, as depicted in Figure 2. The mechanical indicators presented are essential for assessing the appropriateness of the composite material for a range of applications, especially in the context of structural or lightweight panel components. Flexural strength denotes the capacity of a material to resist deformation when subjected to load, specifically its proficiency in enduring bending stress. In addition, the modulus of elasticity serves to characterize the stiffness of a material and delineates the stress-to-strain ratio within the elastic deformation region [14].

Figure 2. Bending Test

Composite Fabrication Process

The preliminary phase in the production of coconut Fiber-reinforced composite materials entails the organization of necessary tools and materials. The separation of coconut coir Fibers into coarse and fine categories is initially conducted, followed by the meticulous alignment of these Fibers utilizing masking tape and paper to ensure uniform placement within the Mold. The preparation of the epoxy resin involves the combination of the resin with a catalyst and promoter, in accordance with the specifications provided by the manufacturer. The mixture is agitated comprehensively until a uniform consistency is achieved, after which it is allowed to stand for approximately 10 minutes to facilitate the natural dissipation of entrapped air bubbles. This step is crucial for guaranteeing the integrity of a high-quality resin-Fiber matrix [15].


Figure 3. Resin Mixing

Subsequently, the granite Mold is treated with a specialized lubricant, referred to as miracle glass, to inhibit the adhesion of the composite material to the Mold surface. Upon the drying of the lubricant, a preliminary layer of resin is applied to the surface of the Mold (Figure 3). The coconut Fibers that have been prepared are distributed uniformly over the resin layer, after which an additional layer of resin is applied. A roller is employed to effectively press the resin into the Fibers, thereby ensuring optimal resin absorption. Ultimately, a second granite plate is positioned atop the initial layer, and a consistent weight—such as a stone—is introduced to guarantee uniform pressure distribution and the attainment of a smooth composite surface (Figure 4). This technique enhances the adhesion between the Fiber and matrix, a factor that is essential for achieving mechanical strength [16].

Figure 4. Resin Application

The composite is subsequently allowed to cure for a duration of 24 to 36 hours, facilitating the complete hardening of the resin and achieving optimal structural integrity [17]. Upon completion of the curing period, the applied load is systematically removed, and the Mold is meticulously disassembled. The composite produced is subsequently sectioned to conform to the standard dimensions required for test specimens utilized in mechanical testing, as depicted in Figure 5. The bending strength test is conducted utilizing a three-point bending method on a Hunta HT-2402 testing machine, with a span length of 36 mm. This procedure guarantees the appropriate preparation of specimens, thereby facilitating the acquisition of precise and reproducible data regarding mechanical performance.

Figure 5. Coir Fiber Composite Specimen

Data Collection and Analysis

Data were obtained directly from the Hunta HT-2402 testing apparatus employing the three-point bending principle. The analysis encompasses the calculation of the Fiber volume fraction, the determination of the resin and hardener requirements, and the evaluation of the Fiber-to-resin ratio in the final composite. The specimens conformed to the dimensions specified in ASTM D790-03, exhibiting a width of 13 mm, a length of 127 mm, and a support span of 35 mm. The epoxy resin utilized exhibited a density of 1.13 g/cm^3, whereas the coconut coir Fiber reinforcement demonstrated a density of 1.15 g/cm^3. Figure 6 provides a comprehensive visual summary of the entire experimental framework.

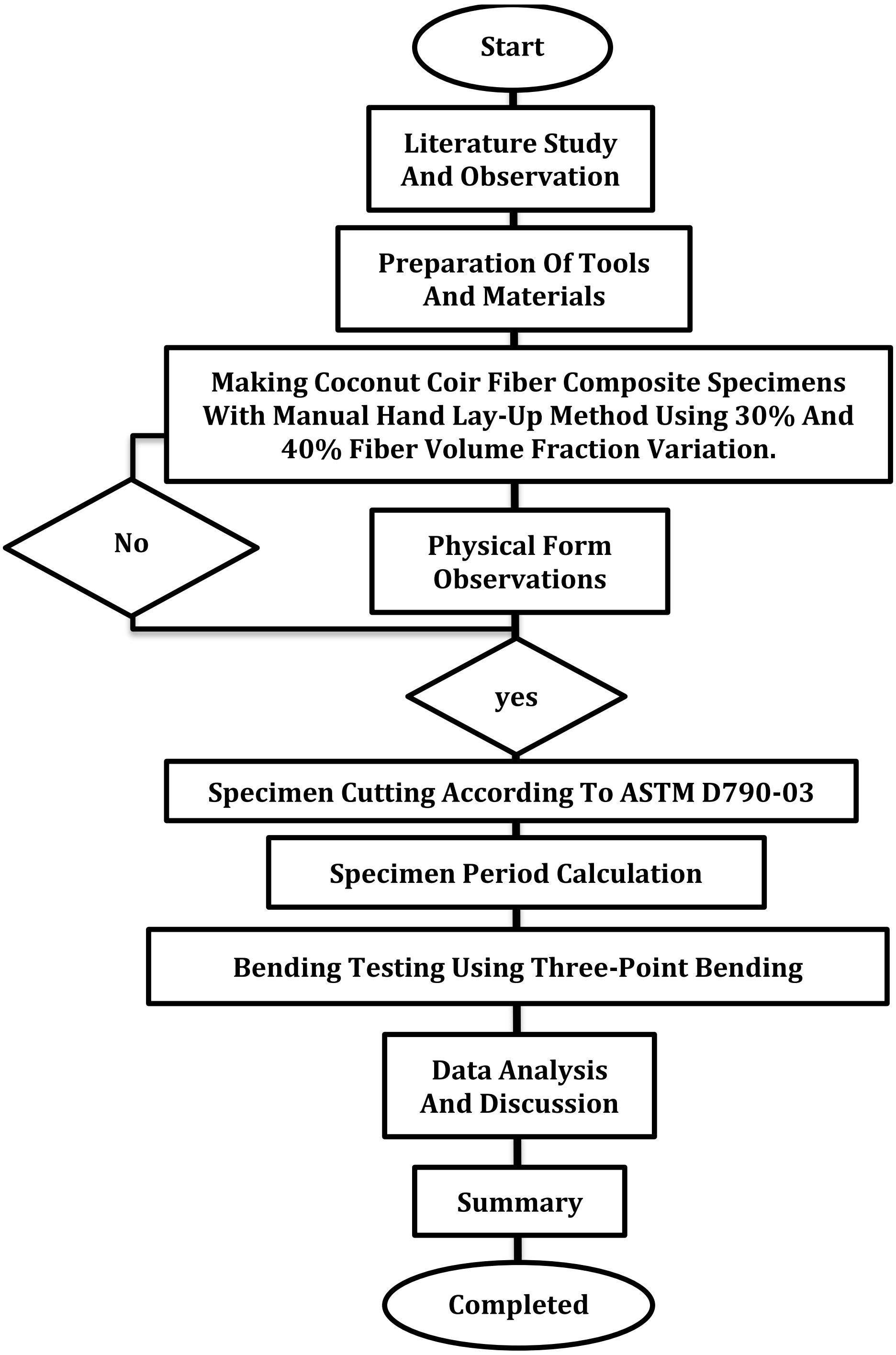

Figure 6. Research Process and Framework

RESULT AND DISCUSSION

The objective of this study was to examine the mechanical performance of composite materials reinforced with coconut coir fibers, which were fabricated utilizing the manual hand lay-up technique. The composite specimens were prepared and sectioned in accordance with the ASTM D790-03 standard for bending tests, featuring dimensions of 127 mm in length and 13 mm in width, as depicted in Figure 6. The experimental procedures, encompassing material mixing, molding, curing, and cutting, were executed within the laboratory of the Mechanical Engineering Department at Universitas Negeri Padang.

The primary test performed was the three-point bending test, which measured the flexural properties of the composites. Two variations of coconut coir fiber volume fraction—30% and 40%—were analyzed. The mold volume was calculated based on its dimensions (12.7 cm × 1.3 cm × 0.5 cm), resulting in a total volume of 8.255 cm^3, which was rounded to 8.26 cm^3 for practical calculations. This volume served as the fixed reference for calculating the volume fractions of the fiber and matrix (resin-hardener).

At a volume fraction of 30%, the calculated fiber volume was determined to be 2.48 cm^3, whereas the matrix volume, consisting of epoxy resin and hardener, was found to be 5.78 cm^3, thereby ensuring that the total volume remained at 8.26 cm^3. At a volume fraction of 40%, the fiber volume was observed to increase to 3.30 cm^3, while the matrix volume correspondingly decreased to 4.96 cm^3. The observed values suggest a negative correlation between the volumes of fiber and matrix, whereas the overall volume of the composite remained unchanged. The maintenance of this consistency is essential for validating comparisons of mechanical performance across different samples.

The bending strength of the specimens, determined via the three-point bending test, was analyzed to assess the impact of increasing fiber volume fraction on the flexural behavior of the composites. The data obtained were presented in quantitative tables and theoretical calculations and were interpreted in relation to values from pertinent literature to substantiate the findings. This analysis establishes the basis for evaluating the impact of increasing the proportion of coconut coir fibers on the mechanical performance of the composite material, with a specific focus on its flexural strength. In the following section, comprehensive test results and a comparative analysis will be provided to investigate the influence of fiber content on resin distribution, internal bonding, and the overall structural performance of the composite.

The required amounts of resin and hardener were calculated based on a 2:1 volume ratio, where the resin constitutes two-thirds and the hardener one-third of the matrix volume. For the 30% fiber volume fraction, with a matrix volume of 5.78 cm^3, the resin volume is 3.90 cm^3, corresponding to a mass of approximately 4.40 g, given the resin's density of 1.13 g/cm^3. The hardener volume is 1.90 cm^3, or 1.70 g, based on its density of 0.875 g/cm^3. For the 40% fiber volume fraction, the matrix volume decreases to 4.96 cm^3, resulting in a resin volume of 3.30 cm^3 (approx. 3.70 g) and a hardener volume of 1.70 cm^3 (approx. 1.50 g). These calculations ensure precision in material composition and are summarized in Table 3.

Table 3. Composite Volume Fraction and Resin-Hardener Calculation

Fiber Volume Fraction	Molding Volume (cm^3)	Fiber Volume (cm^3)	Matrix Volume (cm^3)	Resin Volume (cm^3)	Resin Mass (g)	Hardener Volume (cm^3)	Hardener Mass (g)
30%	8.26	2.48	5.78	3.90	4.40	1.90	1.70
40%	8.26	3.30	4.96	3.30	3.70	1.70	1.50

The three-point bending test results, presented in Table 4, highlight the mechanical performance differences between the 30% and 40% coir fiber volume fractions. The highest force recorded was 630.155 N for the 30% fiber specimen, while the 40% fiber specimen reached a maximum of 524.676 N.

Table 4. Bending Test Results of Coir Fiber Composite Specimens

Volume Fraction	Specimen	Area (mm^2)	Max Force (N)	Modulus (N/mm^2)	Bending Strength (N/mm^2)	Deflection (mm)
40%	1	65	496.527	149.024	66.288	21.94
	2	65	524.676	157.472	70.046	21.99
	3	65	280.755	84.264	37.482	21.96
30%	1	65	630.155	189.130	84.128	22.02
	2	65	461.054	138.377	61.552	21.98
	3	65	384.037	115.262	51.270	21.96
Average 40%	-	-	433.986	130.253	57.939	21.96
Average 30%	-	-	491.749	147.590	65.650	22.00

The results indicate that the composite with a 30% volume fraction exhibited a superior average bending strength of 65.650 N/mm^2 and a modulus of 147.590 N/mm^2, in contrast to the composite with a 40% volume fraction, which demonstrated values of 57.939 N/mm^2 and 130.253 N/mm^2, respectively. The uniform specimen area maintained throughout the tests substantiates that the discrepancies in mechanical performance are predominantly attributable to the material composition and the distribution of resin.

Specimen 3 within the 40% fiber group exhibited a marked decline in performance, recorded at 37.482 N/mm^2. This reduction can be attributed to factors such as suboptimal fiber distribution, fiber aggregation, or insufficient resin impregnation. The diminished matrix volume observed in this fraction (as indicated in Table 3) may have resulted in a decreased availability of resin, thereby heightening the probability of void formation and weak interfacial bonding, which adversely impacted the bending performance. The theoretical advantages of a 40% fiber content, including material efficiency and cost reduction, are counterbalanced by diminished mechanical performance, particularly in bending. This indicates a need for further optimization of the hand lay-up fabrication process to ensure uniform resin distribution and enhanced fiber-matrix adhesion. Figure 7 demonstrates that the refinement of the manufacturing process is crucial prior to the application of high fiber content composites in structural or load-bearing automotive components.

Figure 7. 40% Fraction Specimen

At a 30% fiber volume fraction, the more optimal fiber-to-matrix ratio (2.48 cm^3 fiber and 5.78 cm^3 matrix, as shown in Table 3) allows for more efficient stress transfer between the matrix and the reinforcement. This is evidenced by the highest recorded bending strength of 84.128 N/mm^2 and an average bending modulus of 147.590 N/mm^2, indicating superior stiffness and structural integrity compared to the 40% fraction (Table 4). The performance of the 30% volume fraction composite makes it more suitable for applications requiring moderate to high bending strength, such as lightweight panels or automotive body reinforcements. These findings are visually supported in Figure 8.

Figure 8. 30% Fraction Specimen

Further analysis of the data in Tables 3 and 4 reveals the contribution of coconut coir fiber as a natural reinforcement material to the mechanical strength of the composite. The typical bending strength of pure epoxy resin ranges from 50 to 100 N/mm^2, depending on its formulation and curing. In this study, the 30% fiber composite reached an average bending strength of 65.650 N/mm^2, with a maximum of 84.128 N/mm^2, clearly surpassing the lower bound of pure resin performance. Even the 40% fiber composite, with an average strength of 57.939 N/mm^2 and a peak of 70.046 N/mm^2, remains within a competitive range. This confirms the effectiveness of coir fiber as a reinforcement agent that enhances the composite's structural performance.

The 30% composite exhibited a superior average bending modulus of 147.590 N/mm^2 in comparison to the 40% composite, which recorded a modulus of 130.253 N/mm^2. This observation supports the assertion that moderate fiber volume yields more balanced mechanical properties. Furthermore, both fiber fractions exhibited stable deflection values ranging from 21.94 mm to 22.02 mm, indicating that the inclusion of coir fiber does not negatively impact the material's flexibility; instead, it enhances its structural resilience. The maximum force recorded was notably 630.155 N in the 30% fiber fraction, as illustrated in Figure 9, demonstrating the composite's ability to endure significant flexural loads. The findings indicate the viability of coir fiber-reinforced composites, especially at moderate volume fractions, for implementation in lightweight to medium-load structural applications within industries such as transportation and construction, where there is a growing emphasis on sustainable and cost-effective materials.

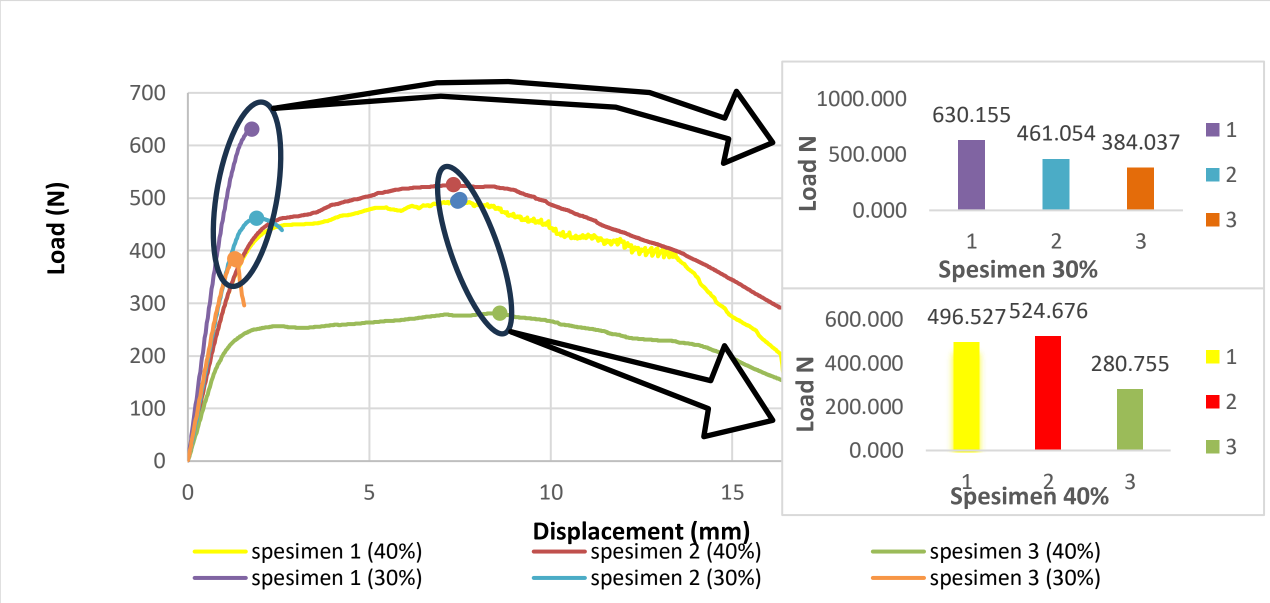

Figure 9. Bending Test Chart

The Manual Hand Lay-Up technique employed in this investigation entailed the manual positioning of coconut coir fibers and the application of epoxy resin at a 2:1 ratio of resin to hardener. This manufacturing method has a substantial impact on the distribution of resin, the impregnation of fibers, and, as a result, the mechanical properties of the composite produced. As presented in Table 4, the specimen area was maintained at a constant value of 65 mm^2, thereby illustrating effective dimensional control. In a similar manner, the deflection values exhibited a narrow range, spanning from 21.94 mm to 22.02 mm, which suggests a consistent degree of flexibility among all specimens.

Nonetheless, a significant differentiation was observed in the analysis of fiber volume fractions. At a fiber volume of 40%, the reduced matrix volume (4.96 cm^3), as indicated in Table 3, may have constrained the degree of resin infiltration into the coir fibers, resulting in uneven fiber wetting. Specimen 3 demonstrates a notably reduced bending strength of 37.482 N/mm^2, which may be attributed to factors such as incomplete impregnation or fiber agglomeration. The coarse and irregular texture of natural coir fiber presents additional challenges for manual resin application, resulting in the formation of localized weak points within the composite matrix.

In contrast, the 30% fiber fraction, with a higher resin volume (5.78 cm^3), allowed for more comprehensive fiber coverage, resulting in improved interfacial bonding and a higher average bending strength (65.650 N/mm^2). This reinforces the notion that an optimal balance between fiber content and matrix volume is critical for mechanical performance in natural fiber composites. While the Manual Hand Lay-Up process is advantageous for low-cost, small-scale fabrication, it presents in resin distribution consistency and fiber alignment. To enhance the mechanical properties and reproducibility of the composite, alternative manufacturing methods such as vacuum infusion or vacuum bagging are recommended. These methods offer more uniform resin impregnation, reduce air entrapment, and minimize porosity, thereby improving both the bending strength and overall structural integrity of the composite material.

CONCLUSION AND RECOMENDATION

Conclusion

This research illustrates that coconut coir Fiber serves as a potent natural reinforcement in composite materials, especially when utilized at a 30% volume fraction. Composites characterized by a 30% Fiber volume fraction demonstrated enhanced mechanical properties, achieving an average bending strength of 65.650 N/mm² and a maximum force of 630.155 N. These values exceeded those observed in composites with a 40% Fiber fraction as well as the conventional bending strength range associated with pure epoxy resin. The findings suggest that a Fiber-to-matrix ratio of 30% is more optimal, facilitating improved stress transfer and enhancing structural integrity. The 40% Fiber volume fraction exhibited a reduction in bending performance, yielding an average strength of 57.939 N/mm². The observed reduction can be ascribed to a diminished resin content and potential inconsistencies in Fiber impregnation, thereby underscoring the constraints of the Manual Hand Lay-Up technique in achieving uniform resin distribution and Fiber alignment at elevated reinforcement levels. The findings highlight the viability of 30% coconut Fiber composites as a sustainable and cost-effective material suitable for applications that necessitate lightweight structures with adequate bending strength. Moreover, the research highlights the necessity for enhanced fabrication methodologies when engaging with elevated Fiber volume fractions to prevent deterioration in mechanical performance.

Recommendation

According to the findings, a volume fraction of 30% coir fiber is advisable for applications that necessitate enhanced bending strength and material stability, including lightweight structural components or load-bearing panels. This fraction offers an optimal equilibrium between mechanical performance and resin distribution, exhibiting enhanced strength and stiffness in comparison to the 40% fraction. Future research should investigate surface treatments, including alkali or silane modification, to enhance fiber-matrix bonding and thereby improve composite performance at elevated fiber contents. Furthermore, the implementation of advanced manufacturing techniques such as Vacuum Infusion or Vacuum Bagging is recommended to enhance resin impregnation and minimize porosity, thereby addressing the limitations identified in the Manual Hand Lay-Up method.

Further investigation should be directed toward optimizing composite formulation by testing intermediate fiber volume fractions (e.g., 35%), evaluating alternative resin-to-hardener ratios, and assessing the influence of resin curing temperatures on mechanical performance. Combining coir fibers with synthetic reinforcements, such as glass or carbon fibers, may also offer hybrid solutions that improve performance without compromising sustainability. These developments could expand the applicability of natural fiber composites in automotive, construction, and other engineering sectors.

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