Manufacture Of Natural Human-Hair Fiber-Reinforced Composites With Combined 0°/±45° Fiber Orientation

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Abstract

Background : Human hair is an abundant biodegradable waste material generated worldwide; however, its potential as a reinforcement material in polymer composites remains largely underutilized despite its favorable tensile properties compared with many natural fibers. Existing studies have primarily focused on simple fiber orientations, while the mechanical performance and reliability of human-hair composites with combined fiber orientations have received limited attention

Purpose : This study aims to evaluate the tensile and flexural properties of a human-hair fiber-reinforced epoxy composite with a combined 0°/±45° symmetric and balanced fiber orientation and to assess the reliability of its mechanical performance using Weibull statistical analysis

Methodology : Human hair fibers were chemically treated with a 5% NaOH solution for 30 minutes and reinforced with an Epoxy Bakelite EPR-174 matrix at a 50:50 fiber-to-matrix weight ratio using the hand lay-up fabrication method. The composite specimens were cured at room temperature for 12 hours and tested according to ASTM D3039 for tensile properties and ASTM D7264 for flexural properties. A Weibull distribution analysis was performed to evaluate the reliability of the measured mechanical properties.

Findings : The developed composite exhibited an average tensile strength of 32.24 MPa and an average flexural strength of 63.13 MPa. Based on Weibull analysis, the predicted strengths at 90% reliability were 31.05 MPa for tensile loading and 60.00 MPa for flexural loading. The combined 0°/±45° fiber orientation effectively distributed the applied load across multiple fiber directions, resulting in lower tensile strength than a fully unidirectional 0° laminate while providing a more balanced mechanical response and enhanced structural reliability**.**

Implications : The findings demonstrate that human-hair fiber composites have significant potential as sustainable and environmentally friendly reinforcement materials for lightweight composite applications. Future studies should investigate additional fiber orientations, optimize fiber volume fractions, and incorporate density characterization following ASTM D792, together with microstructural analyses, to further improve mechanical performance and validate failure mechanisms.

Originality : This study is the first to provide a reliability-based mechanical characterization of a human-hair fiber-reinforced Epoxy Bakelite EPR-174 composite with a combined 0°/±45° symmetric and balanced fiber orientation. The integration of experimental mechanical testing and Weibull reliability analysis offers new insights into the structural performance of biodegradable hair fiber composites for engineering applications**.**

Keywords: *composites; natural fiber; human-hair fiber; alkali treatment; tensile strength*

INTRODUCTION

Human hair is a biodegradable waste material generated in large quantities worldwide, yet it remains largely unused in engineering applications. Its tensile strength, ranging from roughly 150 to 220 MPa, makes it a credible candidate for bio-composite reinforcement (Rao et al., 2017). Recent work has likewise demonstrated that waste human hair, alongside other discarded keratinous fibers such as duck and chicken feathers, can be valorized as reinforcement in epoxy-based composites with favorable mechanical and environmental performance (Nakib et al., 2025).

Hair is a protein filament that grows from follicles in the dermis and is a defining characteristic of mammals; aside from hairless regions of skin, the human body is covered in follicles that produce both coarse terminal hairs and fine vellus hairs. While most research on hair has focused on its growth, morphology, and cosmetic care, it is also a structural biomaterial composed primarily of keratin, a long-chain protein (polymer) built from amino acids. By mass, hair is composed on average of 50.65% carbon, 20.85% oxygen, 17.14% nitrogen, 6.36% hydrogen, and 5.0% sulfur, with constituent amino acids including cystine, serine, glutamine, threonine, glycine, leucine, valine, and arginine (Popescu & Hocker, 2007).

Amin (2012) investigated alkaline treatment of hair fiber prior to composite fabrication, noting that the strength of natural-fiber composites can be improved either through chemical treatment of the fiber or through the addition of coupling agents. NaOH treatment is the most common chemical route because it is inexpensive. Hair fiber used as composite reinforcement is also prone to fiber pull-out, since the fiber's outer cuticle layer impedes bonding with the matrix; alkali treatment with NaOH removes this barrier and improves the mechanical (adhesive) bond between fiber and matrix.

Ningrum (2017) fabricated and characterized hair-fiber composites in an Epoxy EPR-174 matrix with 5% NaOH treatment, providing reference data for the present study. That work examined fiber orientations of 0°, 90°, and ±45° and reported average ultimate tensile strengths of 39.20 MPa for the 0° orientation, 28.47 MPa for ±45°, and 9.50 MPa for 90°.

Building on this prior work, the present study fabricates a natural-fiber-reinforced composite from human-hair clippings—a material otherwise discarded as waste—combined with an epoxy matrix, with the goal of characterizing its weight, stiffness, and strength and thereby reducing hair waste through productive reuse. This paper examines the Hair/Epoxy Bakelite EPR-174 composite at a combined 0° and +45° symmetric and balanced fiber orientation, determined through tensile and three-point bending tests. Because the resulting properties show some scatter, a Weibull distribution analysis was also performed to assess the reliability of the Hair/Epoxy Bakelite EPR-174 composite.

The objective of this research is to characterize the tensile and flexural strength of the combined 0°/±45° human-hair/Epoxy Bakelite EPR-174 composite and to evaluate its statistical reliability. The novelty of this work is twofold. First, it characterizes a combined, symmetric and balanced 0°/±45° fiber architecture that has not previously been reported for this fiber–matrix system, in which earlier work examined only single-direction orientations (Ningrum, 2017). A combined orientation is more representative of practical loading conditions, in which a laminate must resist forces from more than one direction rather than a single axis, making the resulting data more directly usable for component design than single-orientation data alone. Second, this study is the first in this material system to report Weibull-based reliability statistics—including the shape and scale parameters—alongside mean strength values, providing design-relevant, reliability-qualified strength data rather than mean values alone (Statnik et al., 2023).

METHODOLOGY

This study employs an experimental research design. Human-hair clippings sourced from a beauty salon were treated with a 5% NaOH solution for 30 minutes, rinsed, and air-dried, following the procedure summarized in Table 1. Composite specimens were then fabricated by hand lay-up with a combined 0°/±45° symmetric and balanced fiber orientation, using an Epoxy Bakelite EPR-174 matrix at a 50:50 fiber-to-matrix weight fraction, and cured at room temperature for 12 hours. Specimens that did not meet dimensional or visual quality requirements were remade prior to testing.

Table 1. Stages of the Alkali Treatment Process

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No.	Process	Equipment
1	Hair fibers are gathered and tied into bundles to facilitate immersion.	Rubber bands
2	Bundles are submerged in 5% NaOH solution for the specified soaking time.	Plastic container, gloves
3	Fibers are rinsed in clean water and re-soaked to remove residual NaOH.	Rubber gloves
4	Fibers are air-dried at room temperature.	—



Figure 1. Raw human-hair fiber prior to processing

The weight fraction of fiber to matrix governs both the strength and the stiffness of the resulting composite; a 50:50 fiber-to-matrix weight fraction was adopted for all specimens, calculated from the fiber mass (37.2 g), matrix density (2.14 g/cm³), and fiber density (1.17 g/cm³). This yields a required matrix mass of 68.041 g, split equally (1:1 ratio) into 34.02 g of resin and 34.02 g of hardener. The 50:50 fiber-to-matrix weight fraction was selected based on trends reported in the natural-fiber composite literature, where mechanical properties generally improve with increasing fiber content up to roughly 40–60 wt%, with several studies reporting a strength optimum near 50 wt% before resin-starved regions and void formation begin to reduce strength at higher loadings (Seid & Adimass, 2024; Alsuwait et al., 2023). A 50:50 weight fraction was therefore adopted as a literature-informed midpoint balancing reinforcement content against void formation and resin wet-out quality achievable by hand lay-up; the fiber fraction itself was not optimized experimentally in this study and is noted as a direction for future work.

The composite fabrication procedure was as follows: (1) prepare the hair-fiber layer; (2) weigh the fiber mass per the weight-fraction calculation; (3) weigh the matrix mass per the calculation; (4) coat the mold with a release agent and apply a resin layer; (5) lay the hair fibers in the mold according to the specified fiber orientation; (6) apply resin over the fiber layer until the target laminate thickness is reached; (7) cure at room temperature for 12 hours; (8) mark the cured laminate for cutting per ASTM D3039 and ASTM D7264 specimen geometries; and (9) cut the laminate into test specimens.

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Figure 2. Materials and process stages: (1) raw hair fiber, (2) hair bundle prepared for treatment, (3) weighing of materials, (4) treated fiber, (5) fiber laid at 0° in the mold, (6) cured laminate surface, (7) cutting jig, (8) sealed laminate prior to cutting, (9) finished test specimens.

Mechanical testing followed two standards: tensile testing per ASTM D3039/D3039M-17 (ASTM International, 2017) and three-point flexural testing per ASTM D7264/D7264M-07 (ASTM International, 2007). Composite density was estimated using a rule-of-mixtures calculation based on constituent densities and measured specimen mass. To account for scatter in the measured strength values, a two-parameter Weibull distribution analysis was performed on both the tensile and flexural strength data to estimate the strength corresponding to 90% and 50% reliability levels, following the approach used in composite reliability studies (Gibson, 1994).

RESULT AND DISCUSSION

Yu et al. (2016) reported the tensile strength of single human-hair fibers without alkali treatment, ranging from 150 MPa to 270 MPa across five specimens, consistent with the range commonly cited for human hair and providing a useful benchmark for the present composite results.

Table 2. Tensile Test Results for Composite Specimens (0°/±45° Combined, Symmetric and Balanced)

Specimen	Cross-Section (mm²)	Maximum Load (N)	Maximum Stress (MPa)
1	74.676	2428	32.51
2	67.234	2158	32.10
3	63.778	1998	31.33
4	63.960	2112	33.02
Average	—	2174	32.24

Specimen 1 sustained the highest load (2428 N), while specimen 4 recorded the highest ultimate tensile stress, at 33.02 MPa. The average ultimate tensile stress across the four specimens was 32.24 MPa.

Table 3. Three-Point Bending Test Results

Specimen	Cross-Section (mm²)	Max. Force (N)	Deflection (mm)	Max. Stress (MPa)

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1	69.156	98.16	25.16	60.29
2	68.530	101.15	23.77	63.68
3	71.720	105.34	25.00	64.09
4	61.770	90.19	23.03	64.45
5	64.800	95.87	24.11	63.12
Average	—	98.14	24.21	63.13

The average flexural stress across the five specimens was 63.13 MPa, with the highest individual value (64.45 MPa) recorded for specimen 4.The composite specimens exhibited an average density of 1.722 g/cm³, compared with constituent densities of 1.17 g/cm³ for the hair fiber and 2.14 g/cm³ for the Epoxy Bakelite EPR-174 matrix. The measured composite density is sensitive to specimen-level defects such as voids and matrix evaporation during curing; the ASTM D792 displacement method (ASTM International, 1998) would yield a more accurate density value and is recommended for follow-up work.

Because the measured strength values showed some specimen-to-specimen scatter, a Weibull distribution analysis was used to characterize the reliability of the Hair/Epoxy Bakelite EPR-174 composite—that is, the strength level below which the material is statistically unlikely to fail at a given confidence level. For the combined 0°/±45° orientation, the reliability-adjusted ultimate tensile strength was 31.05 MPa at 90% reliability and 32.40 MPa at 50% reliability; the corresponding ultimate flexural strength was 60.00 MPa at 90% reliability and 63.25 MPa at 50% reliability. The 90% reliability level is typically applied to safety-critical structures (e.g., aircraft components), while the 50% level is more representative of applications with lower safety margins, such as wheeled-vehicle or general machine components.

Table 4. Weibull Distribution Parameters for Tensile and Flexural Strength

Property	Weibull Modulus (m)	Scale Parameter (σ_0, MPa)	R^2 (Fit Quality)
Tensile strength	45.3	32.58	0.9985
Flexural strength	36.5	63.96	0.8813

Computed from the raw specimen values in Tables 2 and 3 using Bernard's median-rank approximation and linear regression on $\ln[\ln(1/(1-F))]$ versus $\ln(\sigma)$, this analysis reproduces the 90%/50% reliability strengths already reported above (e.g., 31.00 MPa versus the reported 31.05 MPa at 90% tensile reliability), confirming consistency with the original analysis. The Weibull modulus (m) quantifies the consistency of the failure strength distribution—higher values indicate lower scatter and more uniform fiber–matrix quality, while lower values reflect greater sensitivity to processing defects such as voids or fiber misalignment. Reported Weibull moduli for natural fibers and their composites are generally low relative to synthetic reinforcements, commonly in the range of roughly 2–6 for natural fibers such as coir and bamboo. The moduli obtained here, 45.3 (tensile) and 36.5 (flexural), are notably higher than this typical natural-fiber range, indicating unusually low specimen-to-specimen scatter in the present composite. This result should be interpreted with caution, however: with only four and five specimens respectively, the Weibull modulus estimate carries substantial uncertainty, since a single outlier value can shift the fitted slope considerably at such small sample sizes (see Conclusion for further discussion of this limitation). The comparatively lower R^2 for the flexural fit (0.881 versus 0.999 for tensile) reflects greater deviation from ideal Weibull behavior, likely driven by specimen 1 (60.29 MPa), which fell noticeably below the other four flexural specimens. The scale parameter σ_0 represents the characteristic strength at which approximately 63.2% of specimens are expected to fail, and is consistent with the mean strength values already reported in Tables 2 and 3.

A structural failure is conventionally defined relative to the application: in some cases even minor deformation constitutes failure, while in others only total fracture is considered failure. In a unidirectionally loaded lamina, failure initiates with fiber breakage at the weakest cross-section; as load increases, progressively more fibers break, generally in a staggered rather than simultaneous manner. The dominant failure mode depends on the relative strength of fiber and matrix and on the fiber volume fraction: composites with a lower fiber volume fraction tend toward more brittle fracture, and vice versa.

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Figure 3. Fractured tensile specimens, combined 0°/±45° fiber orientation

As shown in Figure 3, fracture occurred at irregular locations along the gauge length, with arched and non-uniform crack paths. This pattern indicates that the combined 0°/±45° fiber orientation distributed the applied load effectively to the fiber network before fracture, while the character of the fracture surfaces is consistent with brittle failure of the composite.

Table 5. Tensile and Flexural Strength of Hair-Fiber Composites: Present Study vs. Prior Work

Source	Fiber Orientation	Tensile Strength (MPa)	Flexural Strength (MPa)
Ningrum (2017)	0°	39.20	—
Ningrum (2017)	±45°	28.47	—
Ningrum (2017)	90°	9.50	—
Present study	Combined 0°/±45°	32.24	63.13

Differences in tensile and flexural strength among natural-fiber composites can be attributed to several factors: fiber type, since every natural fiber has its own characteristic mechanical properties; fiber orientation and placement, as the direction of fiber relative to the applied load strongly affects load distribution within the laminate; weight fraction, as the ratio of fiber to matrix has a significant influence on composite strength; and alkali treatment, since alkaline treatment and the duration of fiber immersion improve the fiber–matrix bond, with the appropriate soaking time depending on the characteristics of the fiber itself.

The tensile strength obtained in this study for the combined 0°/±45° orientation is lower than the 0° result reported by Ningrum (2017). This is expected: in the combined orientation, the applied tensile load is shared between fibers aligned at 0° and at ±45° within the same laminate, so a smaller fraction of the total fiber volume is oriented to carry load directly along the loading axis, compared with a purely unidirectional 0° laminate.

More recent studies on human-hair fiber composites reinforce these observations. Boyala et al. (2023) fabricated continuous human-hair/polymer composites via vat photopolymerization and similarly found that fiber continuity and orientation govern the resulting mechanical response. Gedam et al. (2023) reported favorable strength-to-weight ratios for hand lay-up human-hair/polymer composites at room-temperature cure, consistent with the present results, while Ashraff Ali et al. (2025) showed that combining human-hair fiber with a second reinforcing phase (cellulose) can further modify tensile and tribological performance relative to a hair-only laminate. At a broader level, recent reviews of natural-fiber-reinforced polymer composites confirm that the fiber–matrix interface and fiber architecture, rather than the fiber type alone, are the dominant factors controlling mechanical performance across this class of materials (Olanrewaju et al., 2025).

Further benchmarking against studies specifically on human-hair/epoxy systems reinforces these findings. Verma and Singh (2019) applied a comparable alkali treatment to human-hair fiber in an epoxy matrix and evaluated tensile, flexural, and compressive behavior across a range of fiber loadings, providing a directly comparable treated-fiber precedent for the present composite. Salih and Al-Zubaydi

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(2021) reported that 15 wt% human-hair reinforcement improved tensile strength by approximately 27% and flexural strength by approximately 25% over an unreinforced epoxy baseline, indicating that even modest hair loadings produce meaningful mechanical gains consistent with the improvements observed in the present combined-orientation laminate. Ansari et al. (2020) further showed that hybridizing human hair with sisal fiber in an epoxy matrix improved tensile performance relative to sisal fiber alone, suggesting fiber hybridization as a promising direction for extending the present single-fiber system in future work. Taken together, these sources situate the present study within an active and growing body of literature on hair-fiber epoxy composites, rather than relying on a single prior comparison point.

Limitations. A limitation of this study is the relatively small number of test specimens (n = 4 for tensile, n = 5 for flexural), which is below the replicate counts typically recommended for high statistical confidence in composite characterization. The Weibull analysis was applied specifically to quantify reliability despite this constraint, but the resulting Weibull parameters themselves carry wider uncertainty with small n—for example, the comparatively high Weibull moduli obtained in this study (Table 4) should be regarded as provisional rather than conclusive given the limited sample size, since a single outlier specimen can noticeably shift the fitted slope at n = 4–5. The fiber weight fraction was likewise fixed at 50:50 based on literature precedent rather than experimentally optimized for this specific fiber–matrix system. Future work should increase the specimen count to at least 10 per test condition to narrow the confidence interval on the Weibull modulus and reliability-based strength predictions, and should experimentally vary the fiber weight fraction to identify the optimum for this material system.

CONCLUSION

This study aimed to characterize the tensile and flexural strength of a human-hair fiber composite with a combined 0°/±45° symmetric and balanced fiber orientation, fabricated from alkali-treated hair fiber in an Epoxy Bakelite EPR-174 matrix by hand lay-up and cured at room temperature. The composite achieved an average tensile strength of 32.24 MPa (maximum 33.02 MPa) and an average flexural strength of 63.13 MPa (maximum 64.45 MPa), with Weibull-predicted strengths at 90% reliability of 31.05 MPa (tensile) and 60.00 MPa (flexural), and at 50% reliability of 32.40 MPa and 63.25 MPa, respectively. The composite density was 1.722 g/cm³. These tensile values are lower than those previously reported for a purely unidirectional 0° hair/epoxy laminate, because the applied load in the combined orientation is distributed across fibers aligned in two directions rather than carried entirely by fibers aligned with the load; fracture surfaces further indicate that the composite fails predominantly in a brittle manner, with the specific failure mode reflecting the combined influence of weight fraction and the relative strength of fiber and matrix. The principal challenge encountered during fabrication was the formation of voids, which were difficult to fully eliminate during hand lay-up, along with difficulty controlling fiber placement; these issues stem from matrix viscosity, the speed of the lay-up process, and the condition of the hair fiber. Future work is recommended to apply the ASTM D792 displacement method for more accurate density measurement and to explore alternative fiber orientations and treatment durations to further improve mechanical performance.

AUTHOR'S CONTRIBUTION

Okta Pianti Rahayu: conceptualization, methodology, specimen fabrication, testing, formal analysis, writing – original draft. Antonius Adi Soetopo: supervision, methodology validation, writing – review and editing. Marta Hayu Raras Sita Rukmika Sari: supervision, validation, writing – review and editing. All authors have read and approved the final manuscript.

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DECLARATION OF COMPETING INTEREST

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