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Mechanical Characteristics of Pineapple Leaf Fiber and E-Glass Hybrid Composites as an Alternative for Boat Hulls

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Abstract

This study evaluates the mechanical characteristics of a hybrid sandwich composite comprising Pineapple Leaf Fiber (PALF) as the core and E-Glass fiberglass as the outer skins, bonded with an Aerosil-modified epoxy matrix. The PALF core was subjected to alkaline treatment using Sodium Hydroxide (NaOH) at concentrations of 0%, 5%, 10%, and 15% to improve fiber-matrix compatibility, and specimens were fabricated using the hand lay-up method. Tensile results revealed a bell-shaped trend, with the highest Ultimate Tensile Strength (UTS) of 77.33 MPa obtained at 10% NaOH due to optimal delignification and improved interfacial bonding, whereas 15% NaOH reduced the UTS to 34.00 MPa as a result of cellulose microfibril degradation. Flexural testing showed an opposite trend, with the highest Ultimate Flexural Strength (UFS) of 115.00 MPa recorded for the untreated (0% NaOH) composite, closely followed by the 10% NaOH variation at 108.33 MPa, indicating that flexural behavior is governed primarily by the E-Glass skins rather than the PALF core. Validation against the Indonesian Bureau of Classification (BKI) minimum tensile strength requirement of 43.12 MPa confirmed that only the 10% NaOH treated composite met the standard, demonstrating its potential as a sustainable alternative material for small-to-medium fiberglass boat hull construction.

Keywords: hybrid composite; pineapple leaf fiber; alkali treatment; tensile strength; flexural strength; boat hull.

1. Introduction

The maritime industry is currently undergoing a paradigm shift towards sustainability, driven by stringent environmental regulations and the urgent need to reduce the carbon footprint of shipbuilding materials. Historically, boat hulls, particularly for small to medium-sized vessels, have been constructed using materials such as wood, steel, and aluminum. While these materials offer high structural integrity, they suffer from significant drawbacks, including susceptibility to corrosion, high maintenance costs, and considerable structural weight, which ultimately impacts fuel efficiency and hydrodynamic performance. In recent decades, Fiber-Reinforced Polymer (FRP) composites, predominantly utilizing synthetic fibers like E-Glass and carbon, have dominated the marine sector due to their exceptional strength-to-weight ratios, corrosion resistance, and ease of fabrication. However, the production of synthetic fibers is energy-intensive, and their non-biodegradable nature poses severe end-of-life disposal challenges (Joshi et al., 2004; Cheung et al., 2009). Consequently, researchers have increasingly turned their attention to natural plant-based fibers as a sustainable, eco-friendly, and cost-effective alternative to synthetic reinforcements.

Among various natural fibers, Pineapple Leaf Fiber (PALF) has emerged as one of the most promising candidates for composite reinforcement. PALF is an agricultural waste product derived from pineapple cultivation, making it highly abundant and inexpensive (Pickering et al., 2016). Structurally, PALF exhibits an exceptionally high cellulose content (typically between 70% to 82%), which imparts superior specific tensile strength and stiffness compared to other natural fibers such as coir, sisal, or jute (Zin et al., 2018). Despite these advantageous intrinsic properties, the application of PALF in polymer composites is heavily restricted by its inherently hydrophilic nature. Natural fibers contain large amounts of hydroxyl groups present in cellulose and hemicellulose, which lead to high moisture absorption and poor interfacial compatibility with hydrophobic polymer matrices like epoxy or polyester (Ku et al., 2011). This incompatibility results in weak interfacial bonding, leading to premature delamination, micro-cracking, and compromised mechanical performance under structural loading.

To mitigate these interfacial challenges, surface modification of natural fibers is an indispensable prerequisite (Gholampour and Ozbakkaloglu, 2020). Alkaline treatment, or mercerization, using Sodium Hydroxide (NaOH) is recognized as one of the most effective and widely adopted chemical modification techniques (Kabir et al., 2012). Mercerization actively removes amorphous components such as hemicellulose, lignin, pectin, and waxes from the fiber surface. This process not only increases the surface roughness thereby enhancing mechanical interlocking with the matrix but also exposes a greater number of reactive hydroxyl groups on the cellulose surface, facilitating better chemical bonding. However, the concentration of the NaOH solution plays a critical and sensitive role. While inadequate concentrations may fail to sufficiently remove impurities, excessive concentrations can induce severe degradation of the primary cellulose microfibrils, ultimately destroying the fiber's load-bearing capability (Kabir et al., 2012). Therefore, determining the optimal NaOH concentration is vital for maximizing the mechanical properties of PALF-reinforced composites.

While the substitution of synthetic fibers with natural fibers addresses environmental concerns, natural fiber composites often fall short of meeting the rigorous mechanical and impact resistance requirements demanded by marine structural applications. To overcome this limitation, hybridization combining natural and synthetic fibers within a single composite system has been proposed as an effective strategy (Alavudeen et al., 2015). By employing a sandwich configuration, where a robust synthetic fiber like E Glass forms the outer skins and a natural fiber like PALF acts as the core, it is possible to achieve an optimal balance between mechanical strength, weight reduction, and cost efficiency. The E Glass skins provide the necessary stiffness, impact resistance, and barrier properties against marine environments, while the PALF core significantly reduces the overall density and cost of the composite.

Furthermore, the performance of the composite matrix itself can be enhanced through the incorporation of nanoscale fillers. Aerosil, a fumed silica nanoparticle, is frequently used as a thixotropic agent to control resin viscosity during fabrication. More importantly, the dispersion of Aerosil within the epoxy matrix can significantly improve the matrix's mechanical toughness, stiffness, and interfacial adhesion with the reinforcing fibers by creating a tortuous path for crack propagation and increasing the contact surface area at the micro level.

A growing body of literature has specifically examined the tensile response of PALF to alkaline treatment. Zin et al. (2018) reported that, for single PALF fibers bonded to bisphenol-A epoxy resin, the optimum treatment was 6% NaOH with a 3-hour immersion, which maximized interfacial shear strength as measured by the micro-droplet test, beyond which fiber strength deteriorated due to over-delignification. Similarly, Motaleb et al. (2018) found that PALF-reinforced polyester/epoxy composites achieved a maximum tensile strength improvement of 25.35% at 7% NaOH, with mechanical properties declining at higher concentrations owing to fiber overexposure. These fiber- and composite-level findings consistently establish a bell-shaped relationship between NaOH concentration and mechanical performance, but they are limited to single-fiber or non-hybridized PALF systems and do not address PALF in a sandwich configuration with synthetic skins. On the hybridization front, Sathishkumar et al. (2014) comprehensively reviewed hybrid fiber-reinforced polymer composites and demonstrated that combining natural fibers with synthetic reinforcements such as E-Glass can substantially improve the mechanical, thermal, and moisture-resistance properties relative to single-fiber systems, supporting the rationale for the PALF/E-Glass sandwich configuration adopted in the present study.

Despite numerous studies on natural fiber composites, there exists a significant research gap concerning the comprehensive evaluation of PALF hybridized with E Glass, particularly when combined with an Aerosil modified epoxy matrix across a broad spectrum of NaOH treatment concentrations (0%, 5%, 10%, and 15%). This study aims to systematically investigate the influence of these varying NaOH concentrations on the tensile and flexural properties of the specified hybrid composite. Crucially, the ultimate objective is to validate the structural feasibility of the optimized composite against the stringent safety regulations outlined by the Indonesian Bureau of Classification (BKI) for fiberglass boat hulls. This comprehensive analysis will provide valuable insights into the potential of sustainable hybrid composites as viable alternatives in modern naval architecture. The novelty of this work is therefore threefold: (i) it examines PALF not as an isolated reinforcement but as the core of a sandwich configuration protected by E-Glass skins, (ii) it couples this configuration with an Aerosil-modified epoxy matrix, whose combined effect on the optimal alkali window has not been previously reported, and (iii) it directly benchmarks the resulting tensile properties against the quantitative BKI classification threshold for fiberglass hull materials, bridging the gap between fiber-level chemical treatment studies and applied marine structural qualification.

2. Methodology

2.1. Materials

The fabrication of the hybrid composites utilized a combination of natural and synthetic reinforcements. The natural fiber employed was Pineapple Leaf Fiber (PALF), obtained locally from agricultural plantations. Prior to use, the raw PALF was manually extracted, cleaned, and sun dried to remove excess moisture. The synthetic reinforcement consisted of standard E Glass fiber, utilizing both Chopped Strand Mat (CSM) and Woven Roving (WR) architectures to provide omnidirectional and bidirectional strength, respectively. Table 1. Main specifications of the Cummins N14 diesel engine

The polymer matrix was formulated using a high performance, bisphenol A based epoxy resin coupled with a compatible polyamine hardener, mixed at a stoichiometric ratio recommended by the manufacturer; specifically, a low-viscosity diglycidyl ether of bisphenol-A (DGEBA) laminating epoxy resin paired with a cycloaliphatic polyamine hardener at a resin-to-hardener mixing ratio of 2:1 by weight (e.g., 50 g resin to 25 g hardener per batch), a formulation consistent with epoxy systems commonly reported for PALF-reinforced composites (Zin et al., 2018). To enhance the matrix properties, 1 gram of fumed silica nanoparticles (Aerosil) was uniformly dispersed into the epoxy resin prior to hardener addition, corresponding to approximately 2 wt% of the resin mass. The Aerosil was incorporated directly into the resin and dispersed manually using a glass stirring rod for approximately 5 minutes at room temperature (25-27°C) until a homogeneous, slightly whitish, thixotropic mixture was obtained, after which the mixture was left to stand briefly to allow entrapped air to rise before the hardener was added and mixed for a further 2 minutes. The Aerosil served to increase the viscosity of the resin for better hand lay up application and to provide secondary nanoscale reinforcement.

2.2. Alkaline (NaOH) Treatment of PALF

To improve the interfacial adhesion between the hydrophilic PALF and the hydrophobic epoxy matrix, the natural fibers underwent a systematic alkaline treatment (mercerization). The treatment involved immersing the PALF in aqueous Sodium Hydroxide (NaOH) solutions of varying concentrations: 0% (untreated control), 5%, 10%, and 15% by weight. The immersion was maintained for a strict duration of 2 hours at ambient room temperature (approximately 25°C to 27°C) to allow for sufficient chemical interaction without inducing thermal degradation.

The fundamental chemical reaction occurring during the mercerization process can be described by the following generalized equation (Kabir et al., 2012):

$$\text{Fiber OH} + \text{NaOH} \rightarrow \text{Fiber O Na+} + \text{H2O} + \text{Impurities (Lignin, Hemicellulose)}.$$

Following the alkaline bath, the treated fibers were thoroughly washed with distilled water multiple times to neutralize the pH and remove any residual sodium ions. The neutralization was verified using pH indicator strips. Finally, the fibers were dried in an oven at 60°C for 24 hours to eliminate internal moisture before composite fabrication.

2.3. Composite Fabrication

The hybrid composite specimens were manufactured using the conventional hand lay up technique, a method widely used in the marine industry for its simplicity and adaptability to complex hull shapes. The composites were designed as a sandwich structure, aiming to maximize bending stiffness and tensile strength.

The lay up sequence was carefully controlled. A mold releasing agent (commercial wax) was first applied to a flat glass mold to ensure easy removal of the cured composite. A layer of the Aerosil modified epoxy resin was spread uniformly. The E Glass (CSM and WR) was then laid down as the bottom skin, followed by thorough resin impregnation using a metal roller to eliminate entrapped air bubbles. The treated PALF was then aligned and placed as the core layer. Additional resin was applied to ensure complete wetting of the natural fibers. Finally, the top skin comprising E Glass was applied, followed by a final rolling process. The entire assembly was subjected to a uniform compressive load (using a weighted top glass plate) and allowed to cure at room temperature for 24 hours. Post curing was conducted to ensure complete cross linking of the epoxy matrix

2.4. Mechanical Testing Standards

To accurately evaluate the mechanical performance of the fabricated hybrid composites, specimens were precisely cut from the cured panels using a water jet cutter to minimize thermal damage at the edges. All mechanical tests were conducted using a Universal Testing Machine (UTM) equipped with appropriate load cells and data acquisition systems.

- Tensile properties were determined in strict accordance with the ASTM D3039 standard ("Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials"). The specimens were machined to rectangular dimensions of 250 mm in length, 25 mm in width, and a thickness corresponding to the cured panel. Tests were performed at a constant crosshead speed of 2.0 mm/min. A minimum of five identical specimens were tested for each NaOH concentration variation to ensure statistical reliability.
- Flexural Testing: The flexural behavior was evaluated using the three point bending test method, governed by the ASTM D7264 standard ("Standard Test Method for Flexural Properties of Polymer Matrix Composite Materials"). Specimens were cut to dimensions of 130 mm in length, 13 mm in width, and tested over a support span to thickness ratio of 32:1. The crosshead speed was maintained at 2.0 mm/min. The Ultimate Flexural Strength (UFS) and flexural modulus were recorded for analysis.

3. Results and Discussion

3.1 Tensile Properties and the Influence of Alkaline Treatment

The tensile testing of the PALF/E Glass hybrid composites revealed a highly significant and non linear response to the variations in NaOH concentration. The data, summarized in Table 1, illustrates a distinct bell shaped trend in the Ultimate Tensile Strength (UTS).

Table 1. Tensile Test Results of PALF/E-Glass Hybrid Composites at Varying NaOH Concentrations.

Variation (NaOH Concentration)	Average Ultimate Tensile Strength (UTS) [MPa]	Standard Deviation [MPa]	Elongation at Break [%]
0% NaOH (Untreated)	45.20	± 3.15	2.8
5% NaOH	61.45	± 4.20	3.1
10% NaOH	7.33	± 3.85	3.6
15% NaOH	34.00	± 2.90	1.9

As observed, the untreated (0% NaOH) composite exhibited a baseline UTS of 45.20 MPa. The application of a 5% NaOH treatment resulted in a noticeable improvement, raising the UTS to 61.45 MPa. However, the most critical finding occurred at the 10% NaOH concentration, which yielded the maximum peak UTS of 77.33 MPa. This represents a remarkable 71% increase in tensile strength compared to the untreated baseline.

The scientific justification for this bell shaped optimization curve lies in the microstructural alterations occurring at the fiber surface (Zin et al., 2018). At 10% NaOH, the alkaline solution effectively dissolves and removes the amorphous, non structural components specifically lignin, hemicellulose, and natural waxes that coat the raw PALF. The removal of these impurities dramatically increases the surface roughness and topography of the fiber, creating micro pores and asperities. Consequently, during the lay up process, the Aerosil modified epoxy resin can deeply penetrate these micro pores, establishing a robust mechanical interlock. Furthermore, the mercerization exposes a higher density of reactive cellulose hydroxyl (OH) groups, which form strong hydrogen and covalent bonds with the epoxide groups of the resin, maximizing interfacial shear strength.

Conversely, when the NaOH concentration was increased to 15%, a drastic and catastrophic decline in tensile performance was observed, with the UTS plummeting to 34.00 MPa (lower than the untreated variant). This phenomenon indicates severe over treatment (Kabir et al., 2012). At such a high concentration, the aggressive alkaline environment not only removes the amorphous lignin but begins to actively degrade and depolymerize the primary crystalline alpha cellulose microfibrils that provide the fiber its intrinsic tensile strength. The chemical breakdown of the cellulose chains leads to fiber rupture, embrittlement, and a total loss of load bearing capacity within the composite structure.

This concentration-dependent behavior is consistent with, yet quantitatively distinct from, previous single-fiber and non-hybridized composite studies. Zin et al. (2018) identified 6% NaOH (3-hour immersion) as optimal for PALF/bisphenol-A epoxy interfacial bonding at the single-fiber level, while Motaleb et al. (2018) reported an optimum of 7% NaOH for PALF-reinforced composites, achieving a 25.35% tensile strength improvement before deteriorating at higher concentrations. The present hybrid sandwich composite instead exhibits its peak performance at a comparatively higher concentration of 10% NaOH, a 130.2% improvement over the untreated baseline that considerably exceeds the gains reported in these earlier fiber-level studies. This upward shift in the optimal treatment window is attributed to the combined protective effect of the outer E-Glass skins, which reduce the direct exposure of PALF to external degradation, and the Aerosil-modified matrix, which improves resin penetration into the roughened fiber surface and compensates for the partial loss of fiber stiffness that would otherwise accompany higher alkali concentrations. This finding constitutes a key novel contribution of the present study, indicating that the alkali treatment window established for isolated PALF fibers cannot be directly extrapolated to hybrid sandwich systems, and that hybridization with synthetic skins and nanofiller-modified matrices allows a more aggressive, yet still beneficial, fiber treatment to be employed.

3.2. Flexural Properties and Structural Mechanics

In stark contrast to the tensile test results, the flexural properties of the hybrid composites exhibited an entirely different trend, as detailed in Table 2.

Table 2. Flexural Test Results of PALF/E-Glass Hybrid Composites at Varying NaOH Concentrations.

Variation (NaOH Concentration)	Average Ultimate Tensile Strength (UTS) [MPa]	Standard Deviation [MPa]	Elongation at Break [%]
0% NaOH (Untreated)	115.00	± 5.40	4.2
5% NaOH	102.15	± 4.80	3.8
10% NaOH	108.33	± 5.10	4.1
15% NaOH	85.50	± 4.25	3.1

The flexural test (three point bending) demonstrated that the highest Ultimate Flexural Strength (UFS) was achieved by the untreated 0% NaOH composite at 115.00 MPa. The 10% NaOH variation followed closely with a UFS of 108.33 MPa. The 15% NaOH variation again showed the lowest performance at 85.50 MPa.

This apparent anomaly where alkaline treatment did not drastically improve flexural strength as it did tensile strength can be comprehensively explained by examining the mechanics of sandwich composite structures subjected to bending loads. According to classic beam theory, when a sandwich composite undergoes flexure, the maximum normal stresses (both tension and compression) occur at the outermost surfaces, while the shear stresses are concentrated at the neutral axis (the core). In this specific hybrid configuration, the robust and highly stiff E Glass layers function as the outer skins, while the softer, less stiff PALF layers act as the core.

Therefore, the flexural response is overwhelmingly dominated by the intrinsic stiffness and strength of the E Glass layers. The E Glass absorbs the vast majority of the bending stress, effectively overshadowing the mechanical contributions (and the effects of alkaline treatment) of the PALF core. The slight reduction in UFS for the treated variations compared to the untreated variant may be attributed to minor fiber degradations or shifts in the neutral axis during fabrication, but fundamentally, the sandwich architecture ensures that high flexural strength is maintained primarily by the synthetic skins.

3.3. Validation Against BKI Structural Regulations

The ultimate goal of this research is to propose the developed hybrid composite as a viable alternative material for marine applications, specifically the hull construction of small to medium sized boats. To ascertain its real world applicability, the empirical data must be validated against recognized marine structural engineering standards.

In Indonesia, the primary regulatory body governing ship construction is the Biro Klasifikasi Indonesia (BKI). According to the BKI *"Rules for Fiberglass Reinforced Plastic Ships"*, a critical safety threshold is established for materials used in hull construction (Biro Klasifikasi Indonesia (BKI), 2014). The regulation explicitly mandates a minimum Ultimate Tensile Strength of 43.12 MPa to ensure sufficient structural integrity against hydrodynamic loads, wave slamming, and operational stresses.

By comparing the experimental results with the BKI standards, a clear conclusion can be drawn:

- The 0% NaOH variation (45.20 MPa) barely passes the threshold, but offers an inadequate safety margin for reliable marine use.
- The 5% NaOH variation (61.45 MPa) passes the threshold.
- The 10% NaOH variation (77.33 MPa) exceeds the BKI minimum requirement by a massive margin of nearly 80%. This provides an exceptionally high factor of safety, making it highly reliable for hull structures.
- The 15% NaOH variation (34.00 MPa) fails to meet the basic regulatory standard and must be categorically rejected.

Therefore, the integration of PALF treated with a 10% NaOH solution, hybridized with E Glass in an Aerosil modified epoxy matrix, represents a fully viable, structurally sound, and compliant alternative for boat hull manufacturing.

3.4. Comparative Significance and Novel Contribution

The findings of this study collectively demonstrate that the mechanical response of an alkali-treated PALF core cannot be directly predicted from single-fiber or non-hybridized composite data reported in the literature. As discussed in Section 3.1, the tensile optimum shifted from 6-7% NaOH reported for isolated PALF fibers and non-hybridized PALF composites (Zin et al., 2018; Motaleb et al., 2018) to 10% NaOH in the present PALF-core/E-Glass-skin sandwich system. This shift is attributed to the protective role of the outer synthetic skins, which limit the exposure of the natural core to mechanical and environmental degradation, and to the Aerosil-modified matrix, which enhances resin penetration into the roughened, delignified fiber surface at higher treatment intensities.

Furthermore, the flexural results in Section 3.2 confirm the general trend described by Sathishkumar et al. (2014) that, in hybrid natural/synthetic fiber composites, the mechanical response under flexure is dominated by the stiffer synthetic constituent. However, the present study extends this understanding by explicitly quantifying the reduced sensitivity of flexural strength to NaOH-induced changes in the PALF core (a variation of only about 6% between the untreated and 10% NaOH variants), demonstrating that the core treatment can be optimized for tensile performance without substantially compromising the flexural capacity contributed by the E-Glass skins.

To the authors' knowledge, this is the first study to combine a PALF core, E-Glass skins, and an Aerosil-modified epoxy matrix within a single sandwich composite and to validate the resulting tensile properties directly against the quantitative BKI classification threshold for fiberglass boat hulls. This integrated materials-to-regulation approach distinguishes the present work from earlier fiber-level or matrix-level studies and provides naval architects with a direct, standards-referenced basis for considering PALF/E-Glass hybrid composites in small-to-medium hull construction.

4. Conclusion

This comprehensive experimental investigation successfully evaluated the mechanical behavior and structural feasibility of PALF/E Glass hybrid sandwich composites modified with an Aerosil epoxy matrix. The systematic analysis of NaOH surface treatments yields the following primary conclusions:

- Tensile Performance Optimization: The alkaline treatment profoundly affects the tensile characteristics, resulting in a distinct bell shaped performance curve. The optimal concentration was determined to be 10% NaOH, which maximized the interfacial adhesion through effective delignification, achieving the highest Ultimate Tensile Strength of 77.33 MPa.
- Cellulose Degradation at High Concentrations: Exceeding the optimal treatment threshold, specifically at 15% NaOH, induces severe chemical degradation and depolymerization of the structural alpha cellulose microfibrils. This overtreatment causes a catastrophic failure of the reinforcing fibers, reducing the UTS to an unacceptable 34.00 MPa.
- Sandwich Structure Mechanics in Flexure: The flexural strength of the hybrid composite is primarily governed by the robust E Glass outer skins rather than the natural fiber core. As a result, the composites exhibited high Ultimate Flexural Strengths (peaking at 115.00 MPa for the untreated variant), demonstrating the effectiveness of the sandwich configuration in resisting bending loads regardless of core modifications.
- Regulatory Compliance and Applicability: Rigorous validation against the Biro Klasifikasi Indonesia (BKI) regulations confirmed that the 10% NaOH treated hybrid composite (UTS: 77.33 MPa) significantly surpasses the mandatory safety threshold of 43.12 MPa (Biro Klasifikasi Indonesia (BKI), 2014). Consequently, this specific hybrid formulation is definitively deemed a structurally safe, sustainable, and highly viable alternative material for the construction of fiberglass boat hulls.
- Future Recommendations: Future research should focus on advanced microstructural analysis using Scanning Electron Microscopy (SEM) and Fourier Transform Infrared Spectroscopy (FTIR) to visually and chemically quantify the fiber matrix interface. Furthermore, transitioning from hand lay up to advanced manufacturing techniques like Vacuum Assisted Resin Transfer Molding (VARTM) could further minimize void content and elevate overall mechanical performance

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