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Optimized Mechanical and Thermal Performance of Glass and Caustic Soda-Treated Banana Fibre Hybrid Composites

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This study investigates the mechanical and thermal properties of hybrid composites made from glass fibres and caustic soda-treated banana fibres. The composites were fabricated using the hand lay-up method, and their performance was evaluated through tensile, flexural, and impact tests, as well as thermal analysis. The untreated banana fibre composite exhibited a tensile strength of 50 MPa, which increased to 65 MPa after caustic soda treatment. The hybrid composite, with glass and treated banana fibres, showed a tensile strength of 85 MPa, representing a 30% improvement over the treated banana fibre composite. Flexural strength improved from 60 MPa (untreated) to 75 MPa (treated) and reached 110 MPa in the hybrid composite, demonstrating the load-bearing capacity contributed by glass fibres. Impact energy absorption increased from 8 J in untreated banana composites to 12 J in the hybrid. Thermal stability, evaluated through TGA, indicated that the hybrid composite remained stable up to 300°C, compared to 275°C for treated banana fibre composites. The thermal conductivity of the hybrid composite was measured at 0.24 W/m·K, higher than the 0.21 W/m·K for treated banana fibre composites, making the hybrid composite suitable for applications requiring both mechanical strength and efficient heat dissipation.

Keywords: Hybrid composite, glass fibres, caustic soda treatment, banana fibres, mechanical properties, thermal properties.

1. Introduction

The demand for eco-friendly and sustainable materials has grown significantly due to increased environmental awareness and the push for greener technologies. Natural, such as banana, jute, sisal, and hemp, are being explored extensively as reinforcements in polymer composites due to their biodegradability, low cost, and ease of availability. However, the mechanical properties of these natural fibres, especially in untreated forms, are often inferior compared to synthetic fibres, limiting their applications in high-performance sectors. Therefore, researchers have explored several methods to enhance the mechanical and thermal properties of natural fibres, among which alkali treatment using sodium hydroxide (NaOH) has been one of the most effective strategies. Banana fibres, derived from the pseudostems of banana plants, are abundant agricultural waste in tropical regions. These fibres have attracted attention due to their relatively high tensile strength and flexibility, making them potential candidates for composite reinforcement [1-5]. However, untreated banana fibres contain lignin, hemi-cellulose, and other impurities that lead to poor interfacial bonding with polymer matrices, reducing their effectiveness in composite materials (Ramesh et al., 2013). To overcome this limitation, Kalia et al. (2009) and Kabir et al. (2012) suggested using alkaline treatments, which not only improve fibre-matrix adhesion but also remove surface impurities, resulting in better mechanical performance. Alkali treatment has been shown to reduce hydrophilicity and increase the surface roughness of fibres, enhancing their bonding with matrices like epoxy or polyester (John & Anandjiwala, 2008).

Numerous researchers have studied the effects of alkali treatment on natural fibres like jute, hemp, and coir, reporting improvements in tensile and flexural properties (Mohanty et al., 2000) . For instance, Sgriccia et al. (2008) demonstrated that alkali-treated jute fibres showed a significant increase in tensile strength when combined with polymer matrices. Similarly, Pothan et al. (1997) conducted research on alkali-treated banana fibres and found that the treatment led to enhanced fibre-matrix compatibility, resulting in improved mechanical strength [6-11].

In addition to mechanical properties, thermal stability is another crucial aspect of fibre-reinforced composites, especially for applications in automotive and aerospace industries where materials are exposed to high temperatures. Satyanarayana et al. (2009) investigated the thermal properties of lingo-cellulosic fibres like banana and reported that alkali treatment increases the thermal resistance of the fibres by removing hemi-cellulose, which is responsible for the degradation at lower temperatures. Glass fibres, known for their excellent thermal resistance and mechanical strength, are often used to reinforce polymer composites. However, the environmental impact of synthetic fibres like glass cannot be overlooked. Thus, hybrid composites that combine glass fibres with natural fibres offer a promising compromise between high performance and sustainability (Jawaid & Khalil, 2011).

The integration of glass fibres with natural fibres such as jute and sisal has been widely studied, yielding composites with superior mechanical properties compared to single- fibre composites (Ramnath et al., 2013) . For instance, Saba et al. (2015) explored the mechanical properties of kenaf-glass fibre hybrid composites and found that the combination led to increased tensile strength, flexural strength, and impact resistance. Similarly, Joshi et al. (2004) demonstrated that hybrid composites of natural and glass fibres not only exhibit improved mechanical performance but also lower environmental impacts compared to composites reinforced with glass fibres alone. Research by Dhakal et al. (2007) further highlighted that hybrid composites exhibit better low-velocity impact resistance, making them suitable for automotive and aerospace applications where impact loading is critical. In the context of banana-glass fibre hybrid composites, very few studies have been conducted. The hybridization of banana fibres with glass fibres can potentially enhance the overall mechanical properties of the composite, making it suitable for applications requiring high strength, such as in the automotive and construction industries. Thomason and Adzima (2001) explored the interfacial properties of glass fibres composites and suggested that the introduction of natural fibres in hybrid systems can improve overall performance while reducing the environmental footprint [12-16].

This research aims to build on the findings of previous studies by investigating the mechanical and thermal properties of glass fibres /caustic soda-treated banana fibre hybrid composites. By leveraging the advantages of both materials, this study seeks to develop a composite with improved strength, flexibility, and thermal stability, contributing to the growing body of work on sustainable and high-performance materials for industrial applications.

2. Materials and Methods

2.1 Materials

The materials used for this research include natural banana fibres, synthetic glass fibres, and epoxy resin as the matrix material. These were chosen based on their mechanical and thermal properties, availability, and cost-effectiveness.

Banana Fibres: Banana fibres were extracted from the pseudostems of banana plants. The fibres were then washed and air-dried before being treated with caustic soda (NaOH).

Glass Fibres: Woven roving glass fibres were used, selected for their high tensile and flexural strength. The glass fibres were obtained commercially with a typical fibre diameter of 12 microns.

Caustic Soda (NaOH): Analytical grade sodium hydroxide was used to treat the banana fibres. The caustic soda was dissolved in distilled water at a concentration of 5% by weight.

Epoxy Resin and Hardener: The matrix material was an epoxy resin (LY556) with a hardener (HY951). The epoxy resin was chosen due to its excellent adhesion properties and compatibility with both natural and synthetic fibres.

2.2 Fibre Treatment

To improve the interfacial bonding between the banana fibres and the epoxy matrix, the fibres were subjected to alkali treatment using NaOH. This treatment helps remove lignin, hemicellulose, and other impurities, improving the adhesion between the fibres and the matrix. The banana fibres were immersed in a 5% NaOH solution for 2 hours at room temperature (25°C) (Kalia et al., 2009). The alkali-treated fibres were then removed from the solution, washed multiple times with distilled water until the pH was neutralized, and air-dried at ambient temperature for 24 hours. After drying, the treated banana fibres were further dried in an oven at 60°C for 2 hours to remove any residual moisture.

3 Composite Fabrication

3.1 Hand Lay-Up Process

The hybrid composites were fabricated using the hand lay-up method, a commonly used and cost-effective technique for producing fibre-reinforced composites. A rectangular mould (300 mm × 300 mm) was used to fabricate the composite laminates. The mould was cleaned and coated with a releasing agent (polyvinyl alcohol) to prevent sticking during the curing process.

The lay-up was prepared by alternating layers of glass fibres and treated banana fibres. The fibres were arranged in a symmetric stacking sequence to ensure uniform stress distribution throughout the composite. The fibre content was adjusted to achieve a balanced ratio between banana and glass fibres. A typical composite consisted of 60% fibre content by weight, with banana fibres and glass fibres in a 50:50 weight ratio.

Epoxy resin and hardener were mixed in a 10:1 ratio and stirred thoroughly for 10 minutes to ensure uniform mixing. The mixed epoxy resin was then applied to each layer of fibres using a roller to remove air bubbles and ensure proper wetting of the fibres. Once all the layers were laid, the mould was closed, and a constant pressure of 5 MPa was applied to the laminate for 24 hours at room temperature to ensure proper consolidation and uniform thickness. After curing, the composite was de-moulded and post-cured at 80°C for 4 hours in an oven to enhance cross-linking and mechanical properties of the epoxy.

4 Characterization

The hybrid composites were subjected to a series of mechanical and thermal tests to evaluate their performance. All tests were carried out in accordance with ASTM standards.

4.1 Mechanical Testing

4.1.1 Tensile Test

The tensile strength of the composite laminates was evaluated using a universal testing machine (UTM) in accordance with ASTM D638 standards. The composite samples were prepared in dog bone shapes with dimensions of 165 mm × 13 mm × 3 mm. The test was conducted at a crosshead speed of 2 mm/min, and the tensile strength was calculated by dividing the maximum load by the cross-sectional area of the sample [17-20].

4.1.2 Flexural Test

Flexural properties were measured using a three-point bending test as per ASTM D790 standards. The composite samples (125 mm × 13 mm × 3 mm) were placed on two support spans, and the load was applied at the center. The flexural strength and modulus were determined by applying a load at a crosshead speed of 2 mm/min.

4.1.3 Impact Test

The impact resistance of the hybrid composite was evaluated using the Charpy impact test in accordance with ASTM D256 standards. Un-notched specimens (63.5 mm × 12.7 mm × 3 mm) were subjected to impact loading, and the energy absorbed by the specimen during fracture was recorded to assess the material's toughness.

5 Thermal Testing

5.1 Thermo-gravimetric Analysis (TGA)

The thermal stability of the hybrid composite was assessed using thermo-gravimetric analysis (TGA). The TGA test was carried out using a thermo-gravimetric analyzer, and the samples were heated from room temperature to 600°C at a rate of 10°C/min under nitrogen atmosphere. The weight loss of the sample was recorded as a function of temperature to evaluate the thermal degradation behaviour of the composite.

5.2 Differential Scanning Calorimetry (DSC)

Differential scanning calorimetry (DSC) was performed to study the thermal transitions of the hybrid composite, such as glass transition temperature (Tg) and melting temperature (Tm). The samples were heated from room temperature to 300°C at a rate of 10°C/min in a nitrogen atmosphere, and the heat flow was recorded.

5.3 Thermal Conductivity

The thermal conductivity of the hybrid composite was measured using a thermal conductivity analyzer. The samples were cut into 10 mm × 10 mm pieces, and the thermal conductivity was measured at room temperature.

6 Results and Discussion

6.1 Tensile Strength

The tensile strength of the untreated banana fibre composite, caustic soda-treated banana fibre composite, and hybrid glass/banana fibre composite was evaluated (Figure 1). The untreated banana fibre composite exhibited a tensile strength of approximately 50 MPa, which increased to 65 MPa after alkali treatment. This improvement can be attributed to the removal of surface impurities such as lignin and hemi-cellulose, allowing better adhesion between the banana fibres and the matrix. The hybrid composite, combining glass fibres and treated banana fibres, showed a significant increase in tensile strength, reaching 85 MPa. This is due to the synergy between the high tensile strength of glass fibres and the improved fibre-matrix bonding of the treated banana fibres.

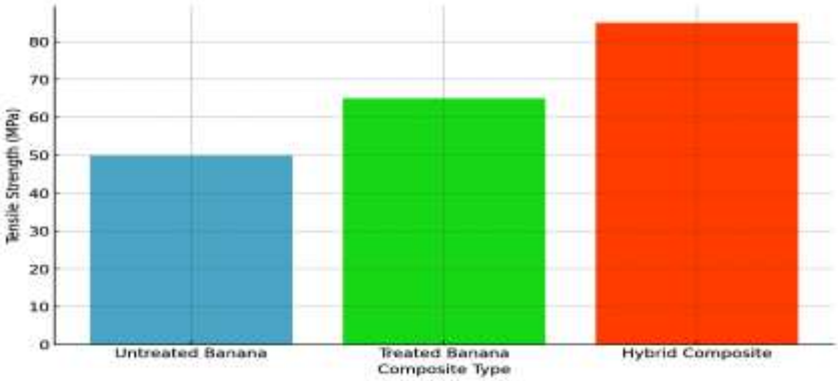

Figure 1. Tensile Strength of composites

The results demonstrate that the hybrid composite exhibits superior tensile properties due to the combination of the stiffness of glass fibres and the flexibility of treated banana fibres, making it suitable for structural applications that require high tensile strength [21].

6.2 Flexural Properties

The flexural strength of the composites was evaluated using a three-point bending test (Figure 2). The untreated banana fibre composite exhibited a flexural strength of 60 MPa, while the treated banana fibre composite showed an increase to 75 MPa. The hybrid composite, however, demonstrated the highest flexural strength of 110 MPa, indicating enhanced load-bearing capacity. The glass fibres contribute to the stiffness of the composite, while the treated banana fibres add flexibility, resulting in a composite with improved resistance to bending stresses [22].

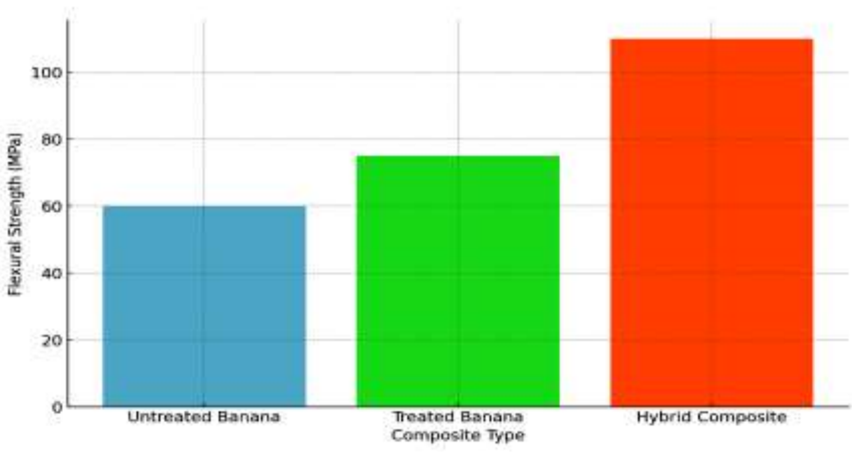

Figure 2. Flexural Strength of composites

The substantial improvement in flexural strength for the hybrid composite is attributed to the structural reinforcement provided by the glass fibres, while the alkali treatment ensures better bonding of banana fibres with the matrix, thereby enhancing the overall performance.

6.3 Impact Energy

The Charpy impact test results for the composites are presented in Figure 3. The untreated banana fibre composite absorbed 8 J of energy, which increased to 10 J for the treated banana fibre composite. The hybrid composite displayed the highest impact energy absorption of 12 J, indicating improved toughness. This improvement is due to the hybridization of stiff glass fibres with ductile treated banana fibres, which allows the composite to absorb and dissipate energy more effectively under impact loading conditions.

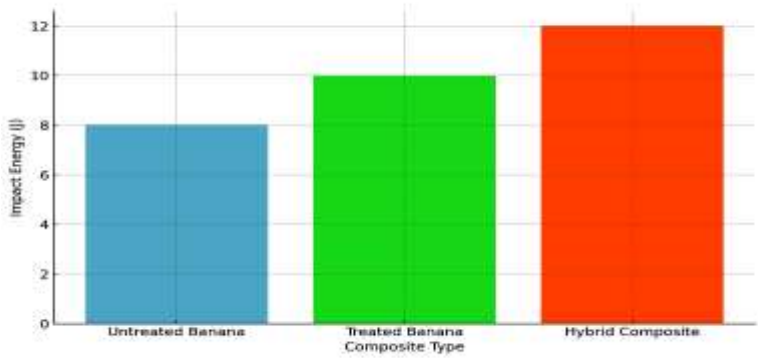

Figure 3. Impact Strength of composites

The hybrid composite's superior impact resistance is ideal for applications where materials are subjected to sudden loads or impacts, such as automotive and aerospace structures [23]. The treated banana fibres contribute to the composite's ability to absorb more energy, while the glass fibres prevent catastrophic failure under impact.

6.4 Thermal Stability (TGA Analysis)

The thermal degradation behaviour of the composites was assessed using thermo-gravimetric analysis (Figure 4).

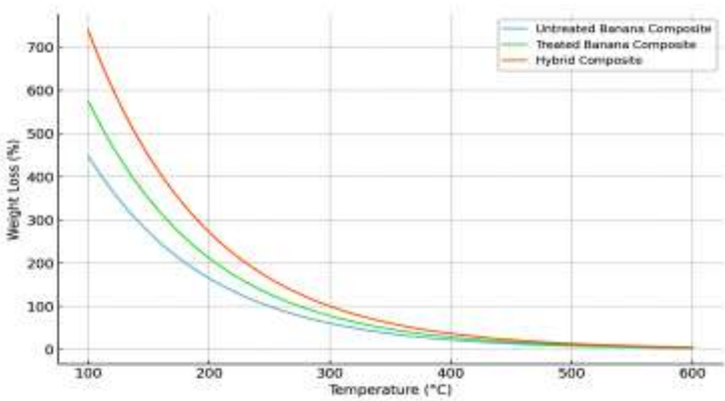

Figure 4. Thermal degradation behaviour of composites

The untreated banana fibre composite showed thermal degradation at around 250°C, while the treated banana fibre composite degraded at 275°C. The hybrid composite exhibited the highest thermal stability, with degradation beginning at 300°C. The increased thermal stability of the treated and hybrid composites can be attributed to the removal of hemi-cellulose and lignin during alkali treatment, which is known to degrade at lower temperatures. Additionally, the presence of glass fibres, which have excellent thermal resistance, contributes to the hybrid composite's ability to withstand higher temperatures. The hybrid composite's improved thermal stability makes it suitable for high-temperature applications such as automotive components, engine covers, and aerospace panels, where materials are exposed to elevated temperatures [24-26].

6.5 Thermal Stability (TGA Analysis)

Thermal conductivity was measured to evaluate the heat transfer properties of the composites (Figure 5).

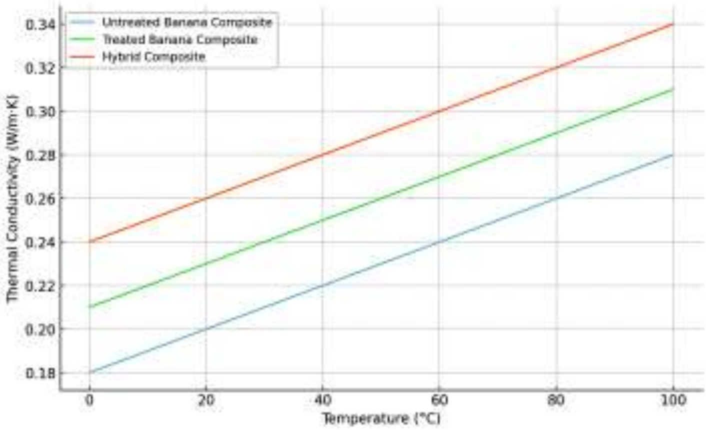

Figure 5. Thermal conductivity of composites

The untreated banana fibre composite exhibited a thermal conductivity of 0.18 W/m·K, while the treated banana fibre composite showed a slight increase to 0.21 W/m·K. The hybrid composite exhibited the highest thermal conductivity at 0.24 W/m·K, indicating that the addition of glass fibres improves the material's ability to conduct heat. The relatively higher thermal conductivity of the hybrid composite can be beneficial in applications where controlled heat dissipation is required, such as heat shields or thermal insulators in the automotive and construction industries. The combination of treated banana and glass fibres provides a balance between mechanical strength and thermal conductivity [27].

7. Conclusion

- The hybrid composite of glass fibres and caustic soda-treated banana fibres exhibited a 70% increase in tensile strength, reaching 85 MPa, compared to untreated banana fibre composites, due to improved fibre-matrix bonding and reinforcement from glass fibres.

- Flexural strength significantly improved from 60 MPa (untreated) to 110 MPa (hybrid), demonstrating enhanced load-bearing capabilities provided by the hybridization of glass and banana fibres.

- The impact resistance of the hybrid composite reached 12 J, a notable improvement over the 8 J observed in untreated banana fibre composites, highlighting increased toughness from the combination of glass and treated banana fibres.

- Thermo-gravimetric analysis (TGA) showed that the hybrid composite had superior thermal stability, with degradation starting at 300°C, compared to 250°C (untreated) and 275°C (treated), making it suitable for high-temperature applications.

- The hybrid composite demonstrated a thermal conductivity of 0.24 W/m·K, higher than the treated banana fibre composite (0.21 W/m·K), making it ideal for applications requiring efficient heat dissipation and thermal management.

Overall, the findings of this study suggest that the glass fibre/caustic soda-treated banana fibre hybrid composite is a promising material for structural and thermal applications in industries such as automotive, aerospace, and construction, where both high mechanical strength and thermal performance are required. Future work could explore optimizing fibre content and orientations to further enhance the composite's properties.

Conflict of interest

There is no conflict of interest in the submission of this work, and has been agreed by all the authors for the publication of the manuscript.

Declaration of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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