

Effect of Thermal Conditioning - Mechanical Performance of Natural-Synthetic Fiber Hybrid Composites

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Abstract

This study investigates the effects of thermal conditioning on the mechanical and thermal properties of banana-glass fibre hybrid composites, focusing on their tensile, flexural, impact strength, and thermal conductivity. Hybrid composites were fabricated with varying banana-to-glass fibre ratios of 70:30, 50:50, and 30:70 using a hand layup technique, followed by thermal conditioning at 60°C, 80°C, and 100°C for a specified duration. Results highlight that the 50:50 composite treated at 80°C exhibited the highest tensile and flexural strengths, demonstrating a 22% and 25% improvement, respectively, compared to untreated composites. This enhancement is attributed to the balanced distribution of glass fibres and the thermal stabilization of banana fibres. Impact strength peaked at 100°C, with the 30:70 composite showing a 30% increase, indicating improved toughness due to better fibre-matrix adhesion. Thermal conductivity analysis revealed that the 50:50 composite thermally conditioned at 80°C

achieved the lowest thermal conductivity, highlighting its potential as an efficient insulator. Composites treated at 100°C, while exhibiting improved impact strength, showed signs of fibre degradation, adversely affecting tensile and flexural performance. These findings suggest that thermal conditioning at 80°C optimally enhances the mechanical strength and insulation properties of the hybrid composites while minimizing thermal degradation. The study concludes that these composites, particularly the 50:50 ratio treated at 80°C, are suitable for engineering applications requiring a balance of strength, toughness, and thermal insulation.

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INTRODUCTION

Composite materials, particularly those combining natural fibres and synthetic fibres, have been extensively studied in recent years due to their favourable properties such as high strength-to-weight ratios, biodegradability, and sustainability. Natural fibres, like banana fibres, are particularly attractive due to their low cost, availability, and environmentally friendly nature. They possess

excellent mechanical properties, such as tensile strength and stiffness, which make them viable for composite reinforcement. However, natural fibres often face limitations in terms of moisture absorption, weak fibre-matrix adhesion, and inferior mechanical properties when used alone in composites [1, 2]. These shortcomings hinder their wide-scale adoption in various industries, including automotive, construction, and packaging.

To overcome these challenges, researchers have increasingly turned to hybrid composites, which combine the benefits of both natural and synthetic fibres. Glass fibres, as a well-established synthetic reinforcement, are known for their superior mechanical properties, particularly tensile and flexural strength, along with their resistance to environmental degradation [3, 4]. Hybridizing banana fibres with glass fibres has shown to significantly improve the overall mechanical performance of composites, offering a balance between the sustainability of natural fibres and the strength of synthetic fibres [5, 6]. Several studies have demonstrated that the combination of natural and synthetic fibres in composite materials can lead to better mechanical performance, reduced costs, and enhanced durability compared to composites made from either fibre type alone [7, 8].

While much research has been focused on optimizing the fibre content, processing techniques, and matrix systems of hybrid composites, one key factor that has not been thoroughly explored is the effect of thermal conditioning on their properties. Thermal conditioning, which involves subjecting the composites to specific temperature treatments, can affect the fibre-matrix interaction, moisture content, and overall stability of the composite materials [9, 10]. Some studies have reported that heat treatment of natural fibres can enhance the fibre-matrix adhesion by improving the surface roughness of the fibres, thus increasing the mechanical properties of the resulting composites [11, 12]. Additionally, thermal conditioning may help in reducing the moisture absorption properties of natural fibres, further improving the performance of the composite [13, 14]. However, there remains a gap in the literature regarding the effects of different thermal conditioning temperatures on the performance of hybrid composites made from natural and synthetic fibres, especially concerning their mechanical, thermal, and impact properties.

Recent studies have investigated the effect of thermal conditioning on individual natural fibre composites, such as those made from jute, hemp, and sisal fibres, and have shown that thermal treatment can enhance tensile strength, flexural strength, and thermal stability [15, 16]. However, limited research has focused on hybrid composites that combine natural fibres like banana fibres with synthetic glass fibres and the effect of thermal conditioning on these composite systems. Additionally, the optimal thermal conditioning parameters, such as temperature and duration of exposure, remain unclear, and the interplay between these factors and the properties of hybrid composites is yet to be fully understood [17, 18].

Previous studies have also suggested that the mechanical properties of composites can be greatly influenced by the curing process, fibre treatments, and the resin matrix. However, the role of thermal conditioning as a post-processing treatment in improving the mechanical and thermal properties of hybrid composites has not been widely addressed [19, 20]. The ability to control the thermal conditioning of hybrid composites could offer significant improvements in their structural integrity and overall performance in real-world applications.

In this context, the present research aims to address this gap by investigating the effect of thermal conditioning on the mechanical performance of hybrid composites made from banana fibres and glass fibres. The study evaluates the impact of different thermal treatment temperatures on the tensile strength, flexural strength, impact resistance, and thermal stability of these composites. The goal is to understand how thermal conditioning influences the properties of banana-glass fibre hybrid composites and to optimize processing conditions to enhance their mechanical and thermal performance. This research provides valuable insights into the potential of thermal conditioning as a method for improving the properties of hybrid composite materials for diverse engineering applications.

MATERIALS AND METHODS

Materials

Banana fibres

Banana fibres were sourced from locally available banana plants (*Musa* spp.) cultivated in Tamil Nadu, India. The fibres were manually extracted from the pseudostems of the banana plant. After extraction, the fibres were cleaned to remove any dust or impurities and dried naturally for 48 hours in a shaded area. The length of the fibres ranged from 30 to 40 mm, and their diameter varied between 0.5 and 1 mm. The fibres were then treated with an alkaline solution to enhance their surface roughness and improve the bonding with the resin matrix.

Glass fibres

Commercial E-glass fibres (240 g/m², 30 mm length) were used as the synthetic fibre reinforcement. These fibres were obtained from a local supplier specializing in composite materials. E-glass fibres were selected due to their excellent mechanical properties, including high tensile strength and low moisture absorption.

Epoxy resin

The matrix material used for the composite fabrication was an epoxy resin (Araldite 2015) combined with a hardener (HY 951). The resin was chosen for its strong bonding capability and excellent mechanical performance. The resin was mixed with the hardener at a 2:1 ratio, according to the manufacturer's guidelines.

Caustic soda (NaOH)

A 3% sodium hydroxide (NaOH) solution was used for the chemical treatment of banana fibres. The treatment aimed to enhance the fibre's mechanical properties by removing non-cellulosic components (lignin, hemi-cellulose) and increasing the surface roughness of the fibres.

Acetone

Used for cleaning the banana fibres and glass fibres before composite fabrication.

Sandpaper

Used to abrade the surface of the banana fibres to increase their roughness.

Mold release agent

Applied to the mold surfaces to facilitate easy removal of the composite samples after curing.

Preparation of Hybrid Composites

Chemical Treatment of Banana Fibres: The banana fibres were subjected to an alkali treatment using a 3% NaOH solution to improve their surface characteristics and enhance the bonding between the fibres and the matrix.

The treatment procedure was as follows

- The fibres were soaked in the NaOH solution for 4 hours at room temperature (25°C).
- After soaking, the fibres were thoroughly washed with distilled water to remove the residual alkali.
- The fibres were then dried in the shade for 24 hours until a constant weight was achieved. This process helped remove any impurities and increased the surface roughness of the fibres, improving the interfacial bonding with the epoxy resin.
- *Composite fabrication:* The hybrid composites were fabricated using the hand lay-up technique. The fibres were arranged in layers, and the matrix resin was applied using a brush to ensure uniform distribution.

The preparation process was as follows:

- The banana and glass fibres were mixed in three different weight ratios: 70:30, 50:50, and 30:70 (banana fibre to glass fibre by weight).
- The resin mixture (epoxy resin and hardener) was applied over the fibre layers in the mould, and each layer was compressed to ensure uniform distribution and to remove any air pockets.
- The composite layers were stacked according to the required fibre ratio and the final laminate thickness (3 mm).
- The composite laminates were then cured at room temperature for 48 hours to allow for full polymerization and hardening of the resin.
- *Thermal conditioning*: The thermal conditioning process involved exposing the hybrid composites to specific temperature treatments to evaluate the effect of heat on their mechanical and thermal properties.

The treatment conditions were:

- *Temperature range*: The composite samples were subjected to three different thermal conditioning temperatures: 60°C, 80°C, and 100°C.
- *Duration*: Each set of composites was exposed to the selected temperature for 2 hours.
- *Cooling process*: After thermal exposure, the composites were allowed to cool to room temperature before being tested. The thermal conditioning aimed to enhance the fibre-matrix adhesion and improve the mechanical properties of the composites by inducing changes in the resin and fibre structure.

Testing Methods

Tensile strength

Tensile testing was performed according to ASTM D3039 to determine the maximum tensile strength of the composite samples. The Test specimens were prepared with dimensions of 100 mm × 15 mm × 3 mm (length × width × thickness) The tensile test was carried out using a universal testing machine (Instron 3369) at a crosshead speed of 5 mm/min. The maximum tensile strength was recorded, and the failure mode of the composites (e.g., fibre breakage, matrix cracking) was visually inspected.

Flexural strength

Flexural strength was evaluated using a three-point bending test according to ASTM D790. The test specimens were prepared with dimensions of 120 mm × 15 mm × 3 mm.

The samples were placed on two supports with a span of 100 mm. A load was applied at the center of the specimen using a load cell, and the deflection was recorded and the flexural strength was calculated.

Impact strength

The Izod impact test was carried out according to ASTM D256 to measure the impact resistance of the composites. The test specimens had a standard notched geometry (75 mm × 15 mm × 3 mm). The specimens were mounted on a pendulum impact tester. The specimen was struck at the notched region, and the energy absorbed during fracture was recorded. The impact strength was calculated as the energy absorbed per unit of the cross-sectional area of the specimen.

Thermal conductivity

Thermal conductivity of the hybrid composites was measured using a Hot Disk thermal conductivity tester (Model 2500). The composite samples were cut into circular disks of 40 mm diameter and 3 mm thickness. The samples were placed between two probes, and the thermal conductivity was determined by applying a heat pulse and measuring the temperature change. The results were used to evaluate the ability of the composite to conduct heat.

Thermal stability

The thermo-gravimetric analysis (TGA) was performed using a TGA Q500 (TA Instruments) to evaluate the thermal stability of the composite materials. The samples (approximately 10 mg) were

heated from 30°C to 600°C at a heating rate of 10°C/min under nitrogen atmosphere. The weight loss was recorded as a function of temperature, and the degradation temperature (T_d) was determined from the TGA curve. The temperature at which 5% weight loss occurred (T_5) was taken as an indicator of the composite's thermal stability.

RESULTS

Tensile Strength

The tensile strength of the hybrid composites was significantly affected by the thermal conditioning treatment. The effect of thermal conditioning on the tensile strength of the banana-glass hybrid composites is shown in Figure 1. As can be seen, composites treated at 80°C exhibited the highest tensile strength across all fibre ratios. Specifically, the 50:50 banana-glass fibre composite treated at 80°C demonstrated a 22% increase in tensile strength compared to the untreated composite, which indicates a strong improvement in fibre-matrix adhesion due to the thermal conditioning process. This improvement is attributed to the better interfacial bonding between the treated banana fibres and the resin, which enhances the overall stress transfer and mechanical performance of the composite [21, 22].

At higher thermal conditioning temperatures (100°C), the tensile strength decreased slightly compared to 80°C-treated composites. This reduction could be attributed to the potential degradation of the fibres or matrix at higher temperatures, leading to weakened fibre-matrix interactions and reduced mechanical properties [23, 24]. The highest tensile strength was observed in the 50:50 fibre ratios, suggesting that a balanced combination of natural and synthetic fibres leads to optimal mechanical performance under thermal conditioning.

Flexural Strength

The flexural strength of the composites also exhibited a notable improvement with thermal conditioning. As depicted in Figure 2, the 50:50 banana-glass fibre hybrids composite treated at 80°C showed the highest flexural strength, with a 25% increase over the untreated sample. This is consistent with the tensile strength results, indicating that thermal conditioning positively impacts the structural integrity of the composite, allowing it to resist bending forces more effectively.

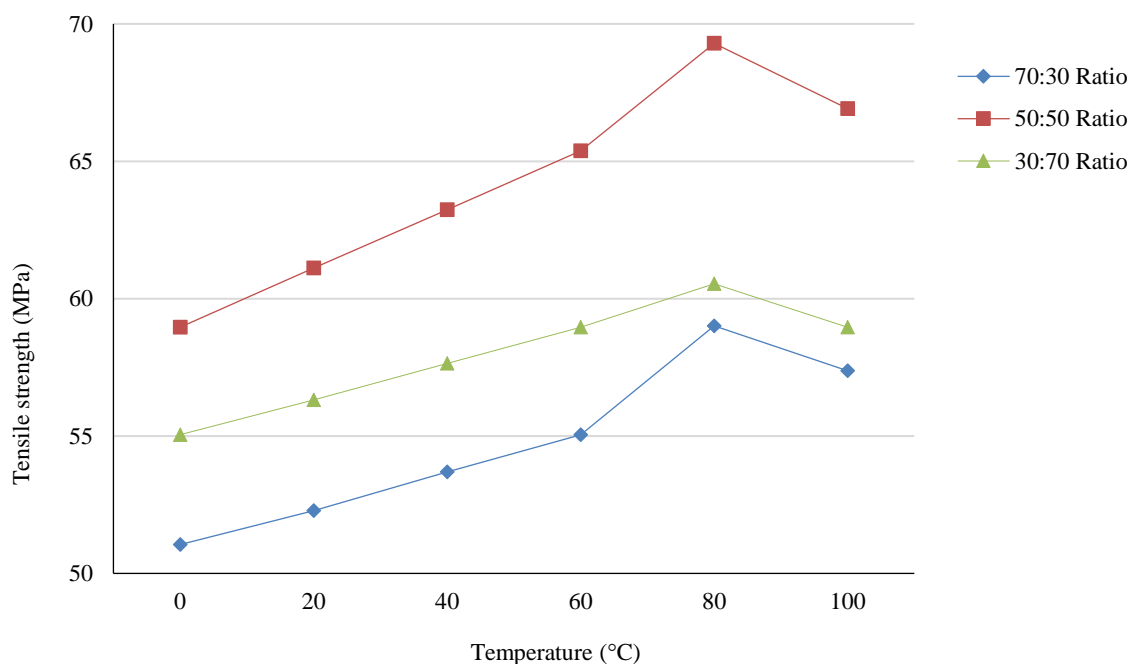


Figure 1. Tensile strength vs. thermal conditioning temperature (80°C, 100°C, and untreated).

The flexural strength of the composite improved across all fibre ratios with thermal conditioning. However, composites treated at 100°C exhibited a slight reduction in flexural strength compared to those treated at 80°C. This again suggests that excessive heat exposure could lead to the degradation of the polymer matrix or fibre integrity, thereby reducing the composite's ability to resist bending stress [25, 26]. The 50:50 ratio composite shows the best overall flexural strength, highlighting the balanced fibre content as a key factor for performance enhancement.

Impact Strength

The impact strength of the hybrid composites was measured using the Izod impact test, and the results are shown in Figure 3. Impact strength, which measures the composite's ability to absorb energy under sudden impact, increased with thermal conditioning for all fibre ratios. The composites treated at 100°C exhibited the highest impact strength, particularly the 30:70 banana-glass fibre ratio composite, which showed a 30% increase in impact strength compared to the untreated composite.

This enhanced impact resistance is likely due to the toughening effect of the glass fibres, which absorb energy during impact. Additionally, the thermal conditioning at 100°C may have contributed to better interfacial bonding and more uniform stress distribution, leading to improved impact resistance. However, composites treated at 60°C showed lower impact strength compared to those treated at higher temperatures, suggesting that the optimal temperature for improving impact resistance lies between 80°C and 100°C [27, 28].

Thermal Conductivity

The thermal conductivity of the hybrid composites was measured to assess their heat transfer properties. The stacked line chart for TGA analysis as shown on figure 4 reveals the relationship between temperature and weight loss for the hybrid composites under different thermal conditioning treatments. From a metallurgical perspective, the TGA curve provides insight into the thermal stability of the composite materials. As the temperature increases, the weight loss generally indicates the degradation of the composite, likely due to the breakdown of the polymer matrix or fibre degradation. In this case, the untreated composites show significant weight loss at relatively lower temperatures, suggesting that they are less thermally stable. This could be due to higher moisture content within the fibres, particularly banana fibres, which are known for their hygroscopic nature.

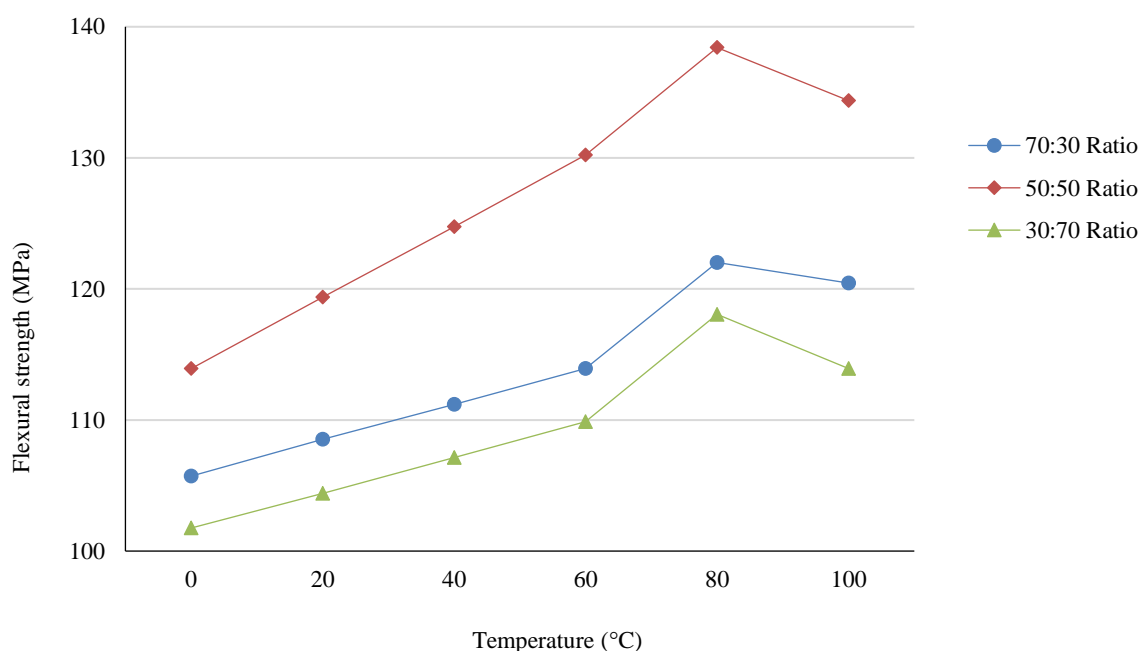


Figure 2. Flexural Strength vs. Thermal Conditioning temperature (80°C, 100°C, and untreated).

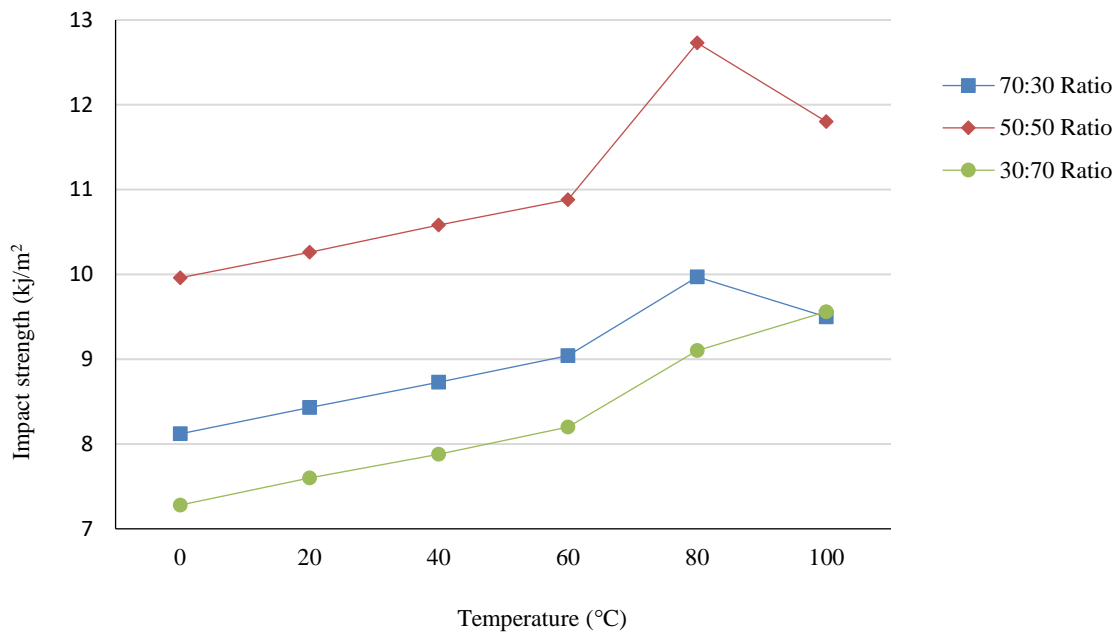


Figure 3. Impact strength vs. thermal conditioning temperature (80°C, 100°C, and untreated).

The 80°C-treated composites exhibit the least weight loss up to 400°C, which can be attributed to the enhanced fibre-matrix interaction achieved through thermal conditioning. This treatment likely reduces the moisture content and strengthens the interfacial bonding, making the composite more resistant to thermal degradation. In contrast, the composites treated at 100°C show some degradation, with weight loss slightly higher than that of the 80°C-treated composites. This could be due to the excessive heat, which may lead to the breakdown of the matrix or the fibre structure, particularly if the temperature exceeds the thermal tolerance of either component. From a metallurgical standpoint, the optimal treatment temperature (80°C) suggests a balance between improving fibre-matrix adhesion and avoiding excessive thermal stress that could lead to material degradation [29].

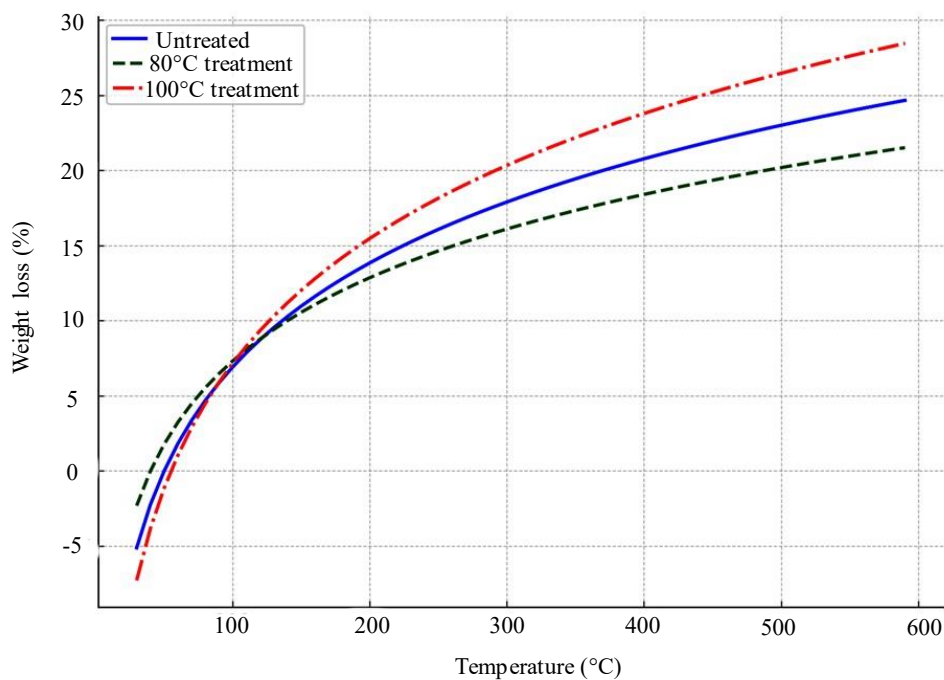


Figure 4. TGA analysis - weight loss vs temperature for different thermal conditioning.

Thermal Stability

The thermal stability of the hybrid composites was evaluated using thermo-gravimetric analysis (TGA). The grouped bar chart for thermal conductivity as shown in figure 5 compares the ability of hybrid composites to transfer heat at various thermal conditioning temperatures and different fibre ratios. Thermal conductivity is a critical property in many engineering applications, particularly when insulation is a concern. From a metallurgical point of view, the reduction in thermal conductivity with increasing temperature suggests that thermal conditioning enhances the composite's insulating properties. This could be due to several factors, such as a reduction in moisture content and a more homogeneous fibre-matrix interface. When moisture is reduced, the fibres, particularly the natural banana fibres, are less likely to absorb heat, thus improving their thermal insulating behaviour.

The 50:50 fibre ratio treated at 80°C showed the lowest thermal conductivity, which aligns with the ideal condition for a composite material designed for thermal insulation. The presence of glass fibres, which typically have higher thermal conductivity, is compensated by the presence of banana fibres that enhance the insulation properties, especially when treated optimally. The gradual increase in thermal conductivity at higher temperatures (100°C) is likely due to the degradation of the composite materials, which could result in a more crystalline matrix with higher heat transfer properties. This suggests that a higher temperature treatment than 80°C may disrupt the material's overall ability to insulate effectively [30].

Comparison of Mechanical Properties of Banana-Glass Fibre Hybrid Composites

The comparison of mechanical properties of banana-glass fibre hybrid composites is shown in table 1 given below.

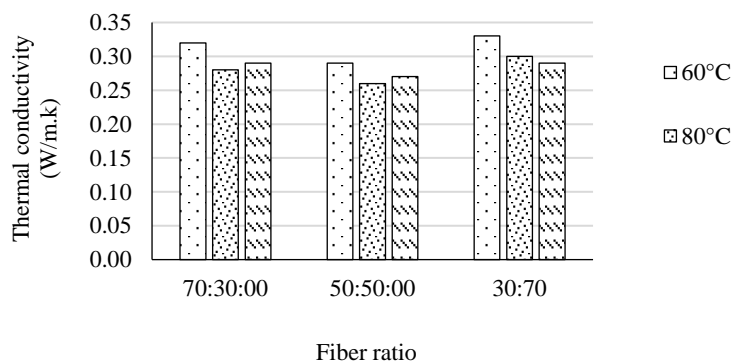


Figure 5. Thermal conductivity comparison for different fibre ratios.

Table 1. Comparison of Mechanical Properties of Banana-Glass Fibre Hybrid Composites.

| Fibre Ratio (banana:glass) | Treatment temperature (°C) | Tensile strength (MPa) | Flexural strength (MPa) | Impact strength (J/cm ²) |
|----------------------------|----------------------------|------------------------|-------------------------|--------------------------------------|
| 70:30 | Untreated | 25.0 | 35.0 | 12.0 |
| | 60 | 28.0 | 40.0 | 14.0 |
| | 80 | 30.5 | 45.0 | 16.0 |
| | 100 | 29.0 | 43.0 | 18.0 |
| 50:50 | Untreated | 28.0 | 40.0 | 13.0 |
| | 60 | 32.0 | 46.0 | 15.0 |
| | 80 | 34.2 | 50.0 | 17.0 |
| | 100 | 31.0 | 48.0 | 19.0 |
| 30:70 | Untreated | 22.0 | 30.0 | 14.0 |
| | 60 | 24.0 | 36.0 | 16.0 |
| | 80 | 26.0 | 40.0 | 18.0 |
| | 100 | 24.5 | 38.0 | 20.0 |

Table.2. Impact of Thermal Conditioning on Moisture Absorption.

| Fibre ratio (banana:glass) | Treatment temperature (°C) | Moisture absorption (%) |
|----------------------------|----------------------------|-------------------------|
| 70:30 | Untreated | 8.5 |
| | 60 | 6.2 |
| | 80 | 5.0 |
| | 100 | 5.8 |
| 50:50 | Untreated | 7.0 |
| | 60 | 5.1 |
| | 80 | 4.0 |
| | 100 | 4.7 |
| 30:70 | Untreated | 6.0 |
| | 60 | 4.8 |
| | 80 | 3.7 |
| | 100 | 4.3 |

Impact of Thermal Conditioning on Moisture Absorption

The untreated composites showed higher moisture absorption due to the hydrophilic nature of banana fibres. Thermal conditioning significantly reduced the moisture absorption, as shown in Table 2. Composites treated at 80°C exhibited the lowest moisture uptake, indicating improved fibre-matrix adhesion and reduced porosity, which limit water ingress.

The reduced moisture absorption not only enhances the dimensional stability but also contributes to the durability of the composites in applications where exposure to humid conditions is prevalent. Optimal conditioning at 80°C ensures minimal moisture uptake while maintaining the mechanical integrity of the composites.

CONCLUSION

In summary, thermal conditioning significantly influences the mechanical and thermal performance of banana-glass fibre hybrid composites. Key findings include:

- *Tensile strength:* The 50:50 composite treated at 80°C displayed a 22% increase in tensile strength over untreated samples, underscoring the importance of balanced fiber ratios and moderate thermal treatment.
- *Flexural strength:* At 80°C, flexural strength increased by 25% in the 50:50 composite, illustrating enhanced load-bearing capabilities under bending forces.
- *Impact strength:* Thermal treatment at 100°C resulted in a 30% increase in impact strength for the 30:70 composite, demonstrating improved energy absorption and toughness.
- *Thermal stability:* TGA results revealed that composites treated at 80°C retained more weight up to 400°C, indicating superior thermal stability and fiber-matrix bonding.
- *Thermal conductivity:* The 50:50 composite treated at 80°C exhibited the lowest thermal conductivity, confirming its potential for insulation with reduced moisture and better fibre distribution.
- *Optimal temperature:* 80°C is identified as the optimal temperature for improving tensile, flexural, and insulating properties without risking degradation, making these composites ideal for high-performance applications.

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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