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Fabrication and Characterization of Bamboo—Epoxy Reinforced Composite for Thermal Insulation

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Abstract

As global warming intensifies, researchers worldwide strive to develop effective ways to reduce heat transfer. Among the natural fiber composites studied extensively in recent decades, bamboo has emerged as a prime candidate for reinforcement. This woody plant offers inherent strengths, biodegradability, and abundant availability. Due to its high cellulose content, its low thermal conductivity establishes bamboo as a thermally resistant material. Its low thermal conductivity, enhanced by a NaOH solution treatment, makes it an excellent thermally resistant material. Researchers incorporated Hollow Glass Microspheres (HGM) and Kaolin fillers into the epoxy matrix to improve the insulating properties of bamboo composites. These fillers substantially enhance thermal resistance, limiting heat transfer. Various compositions, like (30% HGM + 25% Bamboo + 65% Epoxy) and (30% Kaolin + 25% Bamboo + 45% Epoxy), were compared to identify the most efficient thermal insulator. Using Vacuum Assisted Resin Transfer Molding (VARTM) ensures uniform distribution of fillers and resin, creating a structurally sound thermal barrier. These reinforced composites, evaluated using the TOPSIS method, demonstrated their potential as high-performance materials combating heat transfer, offering a promising solution in the battle against climate change.

Keywords

Thermal Insulator, Rooftiles, Hollow Glass Microspheres, Bamboo, Kaolin, Epoxy, VARTM Process, Thermal Conductivity, Mechanical Properties

1. Introduction

In recent years, "green" composites, which are fabricated from plant-derived resin and natural fibers, have received a lot of public attention as one of the most environmentally friendly composite materials. Many comprehensive research projects on the mechanical properties of the "green" composites have been carried out, whereas only a little research on their functionality has been carried out [1]. Therefore, it is highly desirable to develop structural materials from green and renewable biomaterials to replace the synthetic materials involved in the civil engineering and aerospace industries [2].

The objective of this publication is to enhance the mechanical and thermal properties of bamboo-epoxy reinforced composites, with a particular focus on improving their insulation capabilities. Bamboo, a significant biomaterial known for its strength and flexibility, has a long history of use in construction due to its properties. These bamboo fibers, readily available in Asia and parts of the Americas, offer benefits such as good adhesion strength with thermoplastic matrices, lightweight construction, a high aspect ratio, and environmental sustainability through recyclability and biodegradability [3]. However, a challenge in utilizing bamboo fiber-reinforced polymer composites lies in the disparity between the hydrophilic nature of the fiber strands and the hydrophobic characteristics of the polymeric matrices [4].

To overcome the interfacial bonding issues, incorporating coupling agents and surface treatments on fibers are more effective solutions the researchers have been conducting. Several well-known physical and chemical treatments are used for surface modifications such as plasma, hydrothermal, enzymatic, γ-irradiation, ozone, alkali (sodium hydroxide), acid (acetic acid), and polymer (polyvinyl alcohol) [5]. Alkali treatment has been considered one of the most popular and cost-effective methods to obtain high-performance natural fibers. Many studies reported that the alkali treatment is important in determining the structure and properties of natural fibers However, there are a limited number of researches on the bamboo fibers with alkali treatment, especially on the individual bamboo fibers [6]. Hydroxyl groups on the fiber surface, which are hydrophilic, are vastly reduced, which thus increases the fiber's moisture resistance property. The outer surface of bamboo fiber contains a definite amount of hemicellulose, pectin, and lignin that control the rate of water uptake into the fiber core [7].

Epoxy resin (EP) is a widely used thermosetting material in various engineering fields, valued for its excellent mechanical properties, chemical resistance, and thermal insulation capabilities. However, EP does have some limitations, such as its tendency to exhibit poor fracture performance and a high susceptibility to cracking. Consequently, researchers have conducted extensive investigations into improving the mechanical properties of EP by incorporating inorganic particulate fillers or synthetic fibers [8].

In recent years, there has been considerable research interest in the mechanical strength of epoxy resin reinforced with bamboo fibers. These studies have been ongoing for several years and continue to this day. Researchers have conducted a range of tests, including tensile, flexure, and impact tests, on chemically treated bamboo fibers combined with epoxy resin. The consensus from these studies is that the best mechanical properties are achieved when the fiber content is at 25% [9].

High brittleness is a serious problem that can be reduced by incorporating natural or inorganic fiber/filler. The great performance of continuous natural and synthetic fiber reinforced in a polymer matrix is well-known and established. However, these long fiber-based polymer composites have some drawbacks. Major problems are delaminations which can be avoided by the inclusion of micro/nanofiller [10]. The thermal conductivity of composite materials is usually reduced by adding thermal insulation fillers to enhance thermal insulation capabilities. Therefore, the hollow structure of the fillers is an effective way of storing a large amount of air to facilitate the preparation of barrier thermal insulation materials. As a kind of high-temperature-resistant inorganic fibrous thermal insulation material, glass fiber fillers are widely used in the chemical industry, construction, fire protection, and other industrial fields [11]. In theory, hollow glass microspheres have distinct advantages, including a low thermal conductivity coefficient and low density, because they contain air or other gas inside [12]. Hollow glass microspheres (HGM) consist of an outer stiff glass and an inner inert gas, which results in some unique properties such as lightweight, low thermal conductivity, and a low dielectric constant. Based on these properties, HGM has been used in the fabrication of polymer composite materials for different applications. The positive impacts of HGM addition on lowering the thermal conductivity and flammability of composites [13].

Clay-based materials also exhibit very low values of thermal conductivity. A further decrease in conductivity can be achieved by the incorporation of a high volume of porosity into the material [14]. Kaolinite is also an abundant clay mineral, which has been widely applied in ceramics, paper fillers, and as adsorbents in pollution control processes. However, much less research has been done on kaolinite-based polymer nanocomposites. The addition of Kaolin improved the thermal stability and glass-transition temperature (Tg) of the Kaolin/Epoxy composites. The coefficient of thermal expansion (CTE) values decreased with the increase in the Kaolin [15]. To obtain thermal conductivity values below 0.1 W/(m·K), the choice of the solid phase and the type of microstructure becomes essential. Such an objective can be achieved using clay containing kaolinite, which, when combined with a high pore volume fraction, makes it an excellent candidate for the manufacture of an inexpensive insulating material [16].

For the last few decades, the VARTM process has been increasingly used for manufacturing industrial and aerospace components. This process operates at atmospheric pressure and temperature. Also, it is cost-effective, has less processing time, and has a good interior finish [17]. Within the VARTM (Vacuum Assisted Resin Transfer Molding) process, several key parameters significantly influence the manufacturing of complex shapes. Among these parameters, part thickness variation, volume fraction, and pressure gradient play pivotal roles in shaping a wide array of components. Notably, when it comes to the production of substantial composite parts, the reduction of part thickness variation along the filling distance emerges as a highly intricate and demanding task within the VARTM process. Achieving uniformity in part thickness over the entirety of the component, especially in larger applications, requires meticulous attention to these process variables, making it a challenging yet crucial aspect of composite manufacturing. [18]. To find solutions for the preparation of HGMs and resin-based composites with improved properties, this work reports the design of a new preparation method for HGMs and resin-based composites was developed. In this work, HGMs were prepared into a continuous porous preform, after which the resin was impregnated into the same preform using the vacuum-assisted resin transfer moulding (VARTM) method [19].

Among the well-established techniques for multi-criteria decision-making (MCDM), TOPSIS, or the Technique for Order of Preference by Similarity to Ideal Solution, stands out. It is a method that assesses and ranks performance by measuring how closely each option aligns with the ideal solution. Essentially, TOPSIS helps identify the best choice from a set of possible alternatives. Developed by Hwang and Yoon in 1981, TOPSIS is a multi-criteria approach that operates by simultaneously minimizing the distance to the Positive Ideal Solution (PIS) while maximizing the distance from the Negative Ideal Solution (NIS). This method is particularly useful for selecting the most suitable solutions when faced with a finite set of alternatives [20].

The research focuses on creating an innovative composite material by combining hollow glass microspheres (HGM) and kaolin fillers with epoxy resin using vacuum-assisted resin transfer molding (VARTM). The study assesses the material's mechanical and thermal properties, comparing them to traditional concrete roof tiles. The primary goal is to enhance thermal insulation in construction, promoting energy efficiency and sustainability. If successful, this eco-friendly composite material could offer efficient and lightweight alternatives for various construction applications, revolutionizing the industry with its high-performance capabilities.

2. Materials and Methods

2.1. Materials Used

The properties and details of the materials used in this project are described below in **Tables 1-4**. Bamboo fabric was purchased from Etsy fabrics, and IN2 epoxy resin was purchased from Easy Composites. The Kaolin and Hollow glass microspheres were ordered from Castro Composites, Germany.

Table 1. Bamboo fabric properties.

S. No	Property	Value
1	Tensile Strength	150 - 830 MPa
2	Tensile Modulus	15 - 43 GPa
3	Density	0.70 g/cm^3
4	Thermal Conductivity	0.185 W/(m·K)

Table 2. Epoxy resin properties.

S. No	Property	Value
1	Tensile Strength	63.5 - 73.5 MPa
2	Tensile Modulus	2.6 - 3.8 GPa
3	Flexural Modulus	3.35 GPa
4	Density	1.5 g/cm^3
5	Thermal Conductivity	0.19 - 0.25 W/(m·K)

Table 3. Hollow glass microspheres properties.

S. No	Property	Value
1	Type	K20
2	Particle Size	5 - 125 μm
3	Thermal Conductivity	0.038 - 0.060 W/(m·K)
4	Density	0.2 g/cm^3

Table 4. Kaolin properties.

S. No	Property	Value
1	Particle Size	0.2 μm
2	Thermal Conductivity	0.1 - 0.5 W/(m·K)
3	Density	2.64 g/cm^3

2.2. VARTM Process

Vacuum-assisted resin transfer molding (VARTM) is used to prepare a composite manufacturing process. In general, VARTM processes can be categorized into three main stages: sample preparation, infusion step, and impregnation step, a schematic diagram is shown in Figure 1.

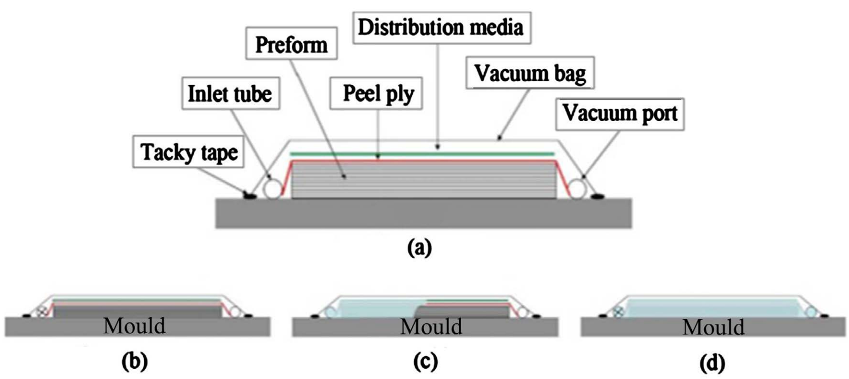

Figure 1. Schematic diagram of VARTM process. (a) Lay-up, (b) Pre-filling, (c) Filling, (d) Post-filling.

This technique defines itself by substituting the top layer of a mold tool with a vacuum bag and peel ply. It employs a sequential arrangement of distribution media and relies on vacuum assistance to facilitate the flow of resin. The procedure involves using a vacuum to allow resin infusion into a fiber layup positioned within a mold tool covered by a vacuum bag. Following impregnation, the composite part undergoes room-temperature curing, with the possibility of an additional post-cure step if desired. The pressure inside the vacuum bag was adjusted, and a chemical reaction was initiated by introducing a hardener to the resin, leading to resin curing. By utilizing vacuum assistance to facilitate the infusion of resin into the fabric layer.

VARTM technique is employed for resin infusion, utilizing a sealed bag with a vacuum to effectively remove air from the composite. Epoxy resin is introduced into the mold through a resin inlet, allowing it to flow through the distribution media and saturate the bamboo fabric and fillers completely. The specimen is left to cure for 48 hours for proper surface finish, allowing the epoxy resin to harden. After the curing period, the specimen is removed from the vacuum seal bag. The pressure in the vacuum bag as well as initiating a chemical reaction by adding a hardener to the resin causes the resin to cure. To prepare the sample for testing and characterization, the composite is cut into the desired dimensions with precision, ensuring consistency and accuracy in subsequent evaluations.

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VARTM technique is employed for resin infusion, utilizing a sealed bag with a vacuum to effectively remove air from the composite, as shown in **Figure 2**.

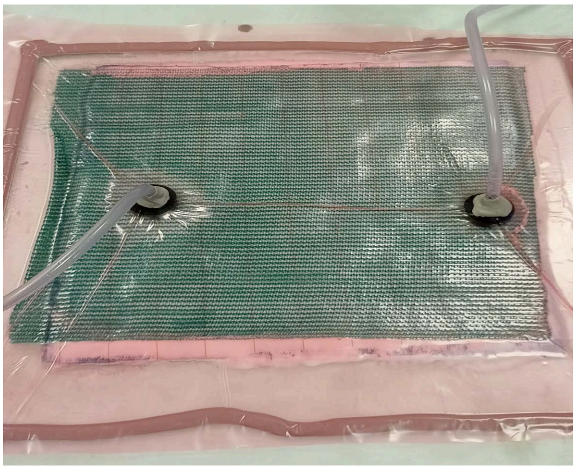

Figure 2. VARTM setup.

Epoxy resin is introduced into the mold through a resin inlet, allowing it to flow through the distribution media and saturate the bamboo fabric and fillers completely. The specimen is left to cure for 48 hours for proper surface finish, allowing the epoxy resin to harden. After the curing period, the specimen is removed from the vacuum seal bag. The pressure in the vacuum bag as well as initiating a chemical reaction by adding a hardener to the resin causes the resin to cure. To prepare the sample for testing and characterization, the composite is cut into the desired dimensions with precision, ensuring consistency and accuracy in subsequent evaluations.

2.3. Manufacturing Process

2.3.1. Surface Treatment

The bamboo fabric is cut into 30 mm × 30 mm sections and subsequently subjected to treatment with NaOH solution. This treatment serves the purpose of reducing the bonding force between strands and minimizing the inter-fibrillar area of the fabric by eliminating lignin and hemicellulose. As a result, the bamboo fabric was distributed more uniformly throughout the matrix, leading to an increased aspect ratio of the fiber in the composite. This enhancement in fiber reinforcement effectiveness can be observed in **Figure 3**.

2.3.2. Sample Preparation and Curing

To ensure uniform distribution for enhanced thermal properties, HGM fillers were poured on the upper layer of the bamboo fabric, thereby avoiding any blockage issues during epoxy resin infusion. Simplifying the fabrication process, a peel ply is positioned over the bamboo fabric and fillers, acting as a release film to prevent adhesion to the composite. A distribution media is then arranged on top of the peel ply, ensuring even resin distribution. To create an air-tight environment, a vacuum seal bag of appropriate size is prepared. The open mold surface is positioned over the composite arrangement, and the vacuum seal bag is closed to eliminate any trapped air, weight distribution of materials shown in **Table 5**.

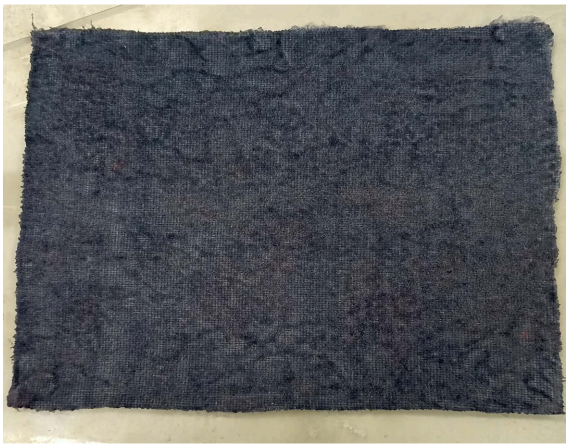

Figure 3. Surface treatment of bamboo fabric with NaOH.

Table 5. Weight of materials used.

Specimen	Weight of Fabric (g)	Weight of Resin (g)	Weight of HGM (g)	Weight of Kaolin (g)	Weight of Composite (g)
S0	78.7	141.8	-	94.5	315
S1	78.7	141.8	94.5	-	315
S2	78.7	173.3	63	-	315
S3	78.7	204.8	31.5	-	315

2.4. Test Equipment and Test Parameters

2.4.1. Flexural Tests

Flexural tests were conducted by the DIN EIN ESO 178 test standard, using a Zwick Universal Testing Machine. Five specimens were made for each composition. The test was run with the following parameters: 0.1 MPa preload, 2 mm/min flexure modulus. Using Test Xpert III testing software, flexural strength, flexural modulus, and elongation at break were measured. For each composition, an average set of five specimens were taken. The examination was conducted on samples measuring 80 × 10 × 5 mm, ensuring a standardized and comprehensive assessment of material performance under flexural forces.

2.4.2. Tensile Tests

Tensile testing was carried out by the DIN EIN ESO 527 test standard. For every composition, a set of five specimens were measured. The test was run with the following parameters: 0.1 N preload, 2 mm/min tensile modulus, and 90 mm span length. Throughout the test, the specimen's force and displacement were meticulously monitored, facilitating the plotting of a comprehensive stress-strain curve. Young's modulus was measured between 0.05 and 0.25% strain. This test was carried out on samples measuring 120 × 10 × 5 mm.

2.4.3. Impact Tests

Charpy impact tests were carried out by the DIN EN ISO 179 test standard. The apparatus was characterized by specific parameters: an impact energy of 4 joules and an impact velocity of 2.9 m/s. The quantification of impact strength was achieved in units of kJ/m^2. In this comprehensive examination, unnotched samples sized 80 mm × 10 mm × 5 mm were employed. The conclusive value was derived from the meticulous averaging of five distinct outcomes, ensuring a robust and reliable assessment of the material's resilience to impact.

2.4.4. Thermal Conductivity Test

The thermal conductivity measurements were conducted using a custom-built measuring cell, following the ASTM E 1225-04. The setup allowed for testing circular samples with a diameter of 50 mm and a thickness of 5 mm. To measure heat flux, three thermistors were positioned in the top meter bar, assuming a constant heat flow through the sample. For accurate data evaluation, a LabView-based program was used to analyze the thermistor readings. To facilitate coupling and reduce interfacial thermal resistance, conductivity was applied. The amount of coupling paste was carefully measured to ensure a consistent application for each measurement. To verify the measuring cell's accuracy, calibration measurements were carried out on isotropic specimens. These calibration tests provided a basis for assessing the reliability of the thermal conductivity measurements. The final value is taken from an average of five measurements.

2.4.5. Thermogravimetric Analysis

The thermal stability of the samples was extensively investigated using the advanced thermogravimetric analyser (TGA4000) from Perkin Elmer. To conduct the analysis, samples of approximately 10 mg in weight were subjected to controlled heating, with the temperature increasing at a rate of 10˚C per minute. The heating process begins at 30˚C and progresses until reaching the final temperature of 600˚C. For an accurate assessment, the TGA analysis was performed in a carefully controlled nitrogen atmosphere, maintaining a consistent nitrogen flow rate of 20 mL/min throughout the experiment. This nitrogen environment ensured the elimination of any potential interference from other reactive gases during the thermal degradation process. Sample weight loss as a function of temperature was measured and plotted.

2.5. TOPSIS Method

The TOPSIS method, known as the technique for order of preference by similarity to an ideal solution, is widely used in multi-criteria decision analysis. It assesses alternatives by considering their closeness to the best possible outcome and their distance from the worst scenario across various criteria. The key objective of TOPSIS is to pinpoint the top-ranked alternative by comparing it comprehensively against all others within a set of simulations. This method provides a systematic and objective approach to making complex decisions, ensuring the selection of the most optimal.

Based on the weights, the equation for the Weight Normalization Decision Matrix is given by

$$A_{ij}\,(\text{or})\quad a_{ij} = W_j \frac{x_{ij}}{\sqrt{\sum_{x=1}^{6} x_{ij}^2}} \tag{1}$$

where W_j—weight of the criteria and x_{ij}—parameter (property) values.

The positive ideal solution A^+ contains the largest numbers of the first, second, and third column of A, and the smallest numbers of the fourth and fifth column of A.

The negative ideal solution A^- contains the smallest numbers of the first, second and third column of A, and the greatest numbers of the fourth and fifth column of A.

The positive and negative separation measure is calculated by using the formulas.

$$S_i^+ = \sqrt{\sum_{j=1}^{n}\left(A_{ij} - A_j^+\right)^2} \tag{2}$$

$$S_i^- = \sqrt{\sum_{j=1}^{n}\left(A_{ij} - A_j^-\right)^2} \tag{3}$$

where A_{ij}—normalized parameter values, A^+—positive ideal solution and A^-—negative ideal solution.

Performance index (P_i) decides the best and worst solutions from the set of alternatives. The equation to calculate this is given by

$$P_i = \frac{S_i^-}{S_i^+ + S_i^-} \tag{4}$$

where, S_i^+ —positive separation measure and S_i^- —negative separation measure.

Finally, the ranking of the attribute is given by the highest performance index to the lowest closeness factor.

3. Results

3.1. Flexural Tests Results

The results of the flexural test show improvements in flexural strength and modulus for specimen S1. The flexural strength and modulus increased with an increase in the weight percentage of HGM filler in the composite. Figure 4 and Figure 5 depict the values of flexural modulus and flexural strength. S1 specimen has the highest values, *i.e.*, 4431 MPa and 51.3 MPa, respectively. On the other hand, S0 specimen exhibits values of 3800 MPa and 38.96 MPa, respectively. Table 6 depicts the values of flexural modulus (E_f) and flexural strength (σ_{fm}), there is an increase of flexural modulus by 14.24% when compared between S1 and S0. The percentage of flexural strength increase between S1 and S0 is 24.05%.

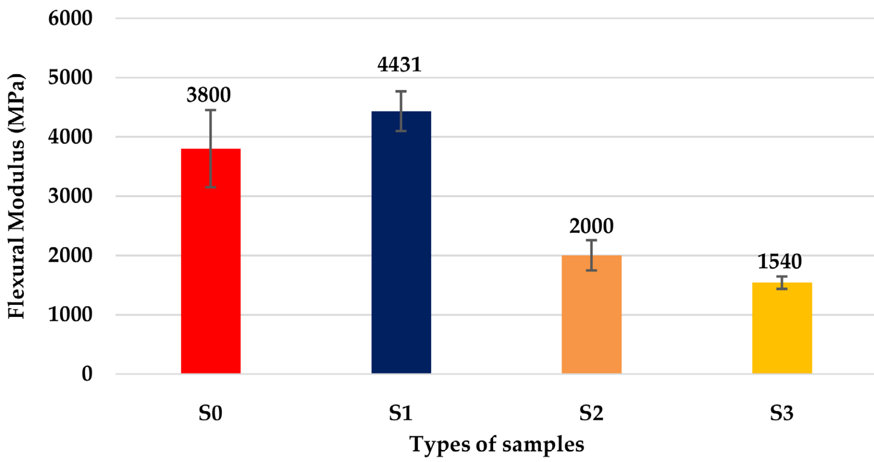

Figure 4. Comparison of flexural modulus of bamboo-epoxy composite with different compositions of HGM and Kaolin fillers.

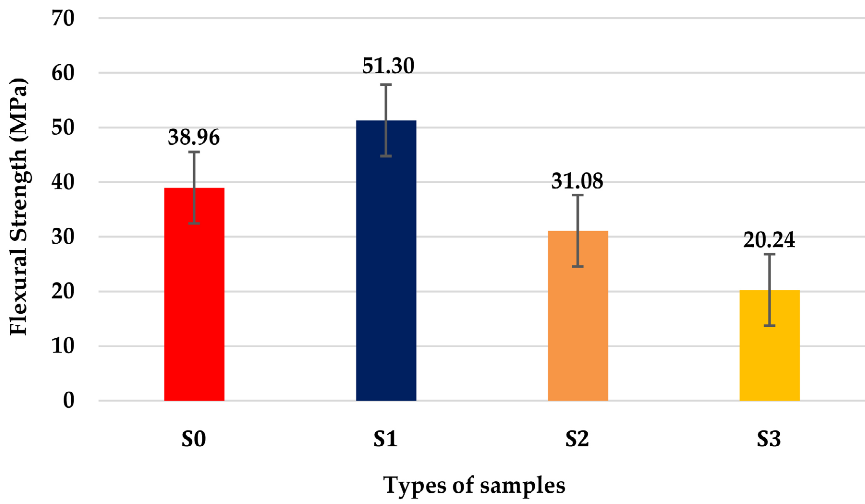

Figure 5. Comparison of flexural strength of bamboo-epoxy composite with different compositions of HGM and Kaolin fillers.

Table 6. Results of flexural tests.

Specimen	E_f [MPa]	σ_{fm} [MPa]
S0	3800 ± 320	38.96 ± 2.5
S1	4431 ± 165	51.30 ± 2.0
S2	2000 ± 125	31.08 ± 1.5
S3	1540 ± 50.5	20.24 ± 2.0

3.2. Tensile Tests Results

Figure 6 and **Figure 7** show the results of the tensile test. A bamboo-epoxy composite with 30% kaolin filler has a very high Young's modulus. On comparing S3 to S2, S2 to S1, and S1 to S0, the young's modulus increased by 33.57%, 15.41%, and 20.28%, respectively. The highest tensile strength was also seen in S0. Similarly, tensile strength of S3 to S2, S2 to S1, and S1 to S0 increased by 28.36%, 19.31%, and 18.20%, respectively. Due to its higher ductility than HGM filler composites, kaolin exhibits a larger percentage of tensile strength and modulus. The comparison of young's modulus (E_t) and tensile strength (σ_m) results is shown in **Table 7**.

Table 7. Results of tensile tests.

Specimen	E_t [MPa]	σ_m [MPa]
S0	2376 ± 175	23.67 ± 0.5
S1	1894 ± 90.5	19.36 ± 0.4
S2	1602 ± 180	15.62 ± 0.8
S3	1064 ± 110	11.19 ± 0.5

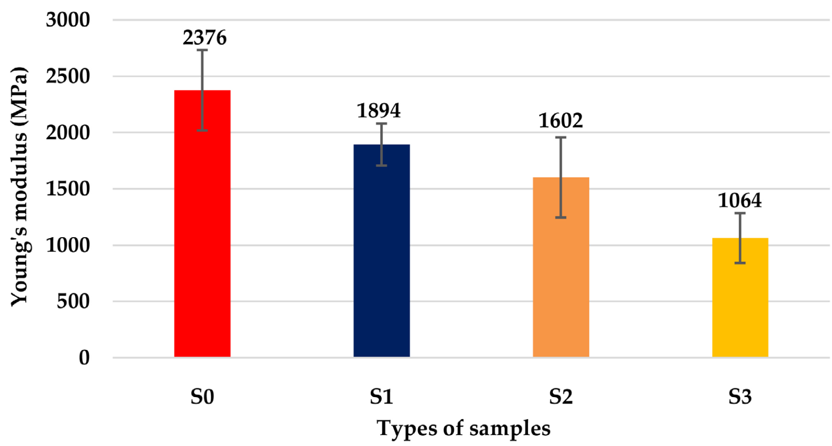

Figure 6. Comparison of young's modulus of bamboo-epoxy composite with different compositions of HGM and Kaolin fillers.

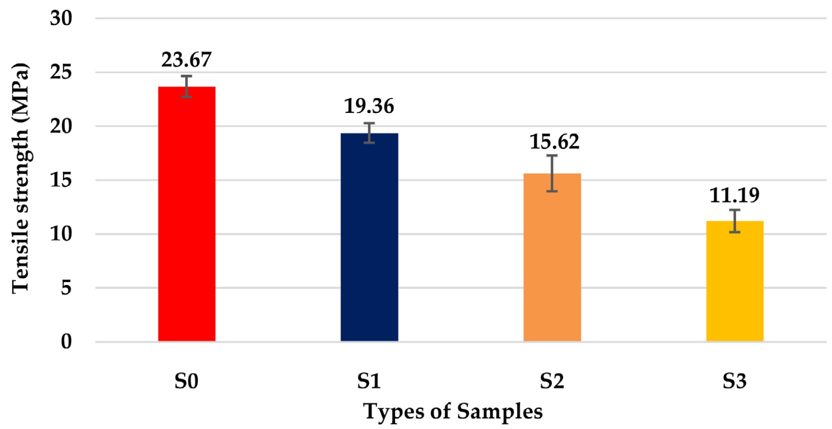

Figure 7. Comparison of tensile strength of bamboo-epoxy composite with different compositions of HGM and Kaolin fillers.

3.3. Impact Tests Results

HGM filler exhibits lower impact strength due to its high capacity for nucleation during crystallization. Figure 8 represents the impact strength of the specimens. As filler content decreased, the energy absorption rate showed a notable increase. Among all the specimens, S3 displayed the highest impact strength, impressively absorbing 5.03 kJ/m^2 of energy which is 6.63% more than the energy absorbed by S2 at 4.7 kJ/m^2. On the other hand, specimens S1 and S0 exhibited impact strengths of 3.64 kJ/m^2 and 3.62 kJ/m^2, respectively. The difference in Impact strength between S1 and S0 amounted to 0.63%.

3.4. Thermal Conductivity Results

Figure 9 provides insightful data on thermal conductivity in the composite. As filler content increases, thermal conductivity decreases, resembling insulation behavior, showing a direct correlation. For instance, the 30% HGM and 45% epoxy resin specimens have the highest values: S1 (0.005 W/(m·K)), S2 (0.016 W/(m·K)), and S3 (0.042 W/(m·K)). In comparison, the 30% Kaolin and 45%

epoxy resin composite has a thermal conductivity of 0.054 W/(m·K) for S0, which is 90.74% higher than S1's thermal conductivity.

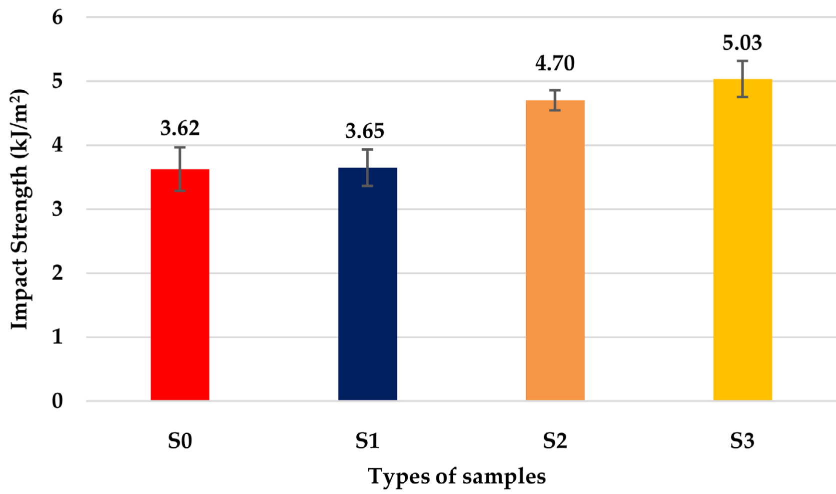

Figure 8. Comparison of impact strength of bamboo-epoxy composite with different compositions of HGM and Kaolin fillers.

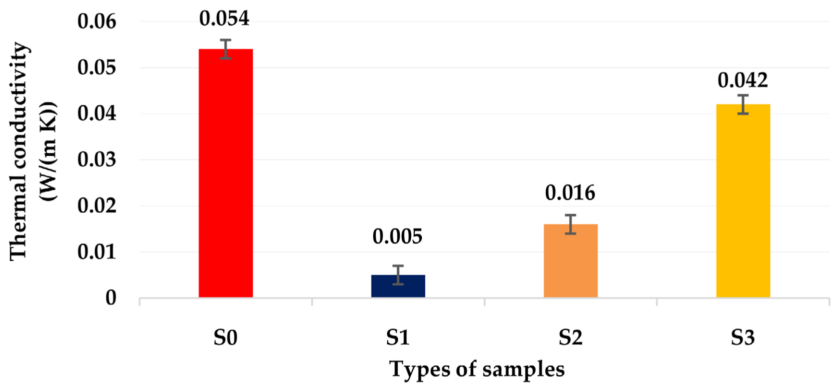

Figure 9. Comparison of thermal conductivity of bamboo-epoxy composite with different compositions of HGM and Kaolin fillers.

3.5. Thermogravimetric Analysis Results

Thermogravimetric Analysis (TGA) was used to investigate the thermal degradation behavior of bamboo epoxy composites containing various proportions of filler. This experiment was carried out by observing changes in weight percentage relative to temperature. The characteristic thermal parameters chosen were the onset temperature, which is the initial weight loss temperature, and the maximum degradation rate temperature obtained from the peak of DTG thermograms. Specimen S0 onset temperature was shown around 335˚C, while for S1, S2, S3 specimens were found 336˚C, 308˚C, and 239˚C, respectively. Graphical representation in Figure 10 illustrates the temperature degradation of 30% HGM, 20% HGM, and 10% HGM filler composites, along with 30% Kaolin. This observed trend suggests that an increase in filler content within the epoxy resin contributes to the enhanced thermal stability of the specimens.

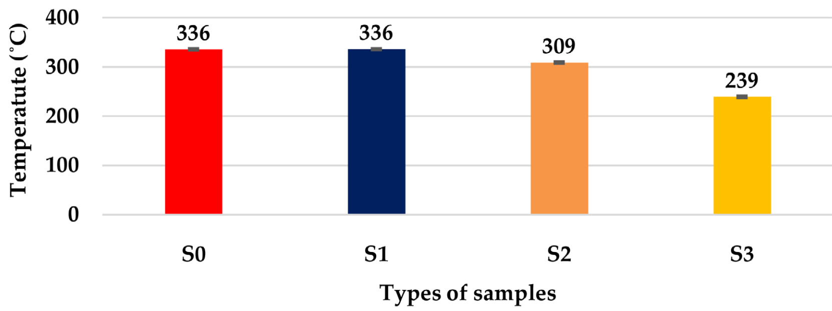

Figure 10. Comparison of temperature degradation of bamboo-epoxy composite with different compositions of HGM and Kaolin fillers.

4. Discussion

4.1. Discussion of Results

The results of this comprehensive study elucidate a compelling relationship between the concentration of HGM filler and the substantial enhancement in the thermal insulation properties of bamboo epoxy composites. The proportion of HGM filler is directly proportional to the enhancement of thermal insulation. Increasing the HGM content up to 30% (S1), led to a significant reduction in thermal conductivity, exhibiting its potential as an efficient thermal insulator. Conversely, the composite containing 30% kaolin (S0) exhibited a distinct thermal conductivity measurement, suggesting the importance of filler selection in tailoring the thermal properties of these composites. Furthermore, as the filler content decreased, the composites exhibited thermal degradation at an earlier stage. The thermal degradation temperatures for the S0 and S1 specimens were quite similar, measuring at approximately 335˚C and 336˚C, respectively.

The mechanical tests through flexural and tensile experiments unveiled the influence of filler quantity on the composite's strength and modulus. Notably, S2 and S3 specimens displayed lower mechanical performance, while 30% of Kaolin filler specimens exhibited competitive results, particularly in the tensile tests. 30% HGM filler specimens exhibited remarkable properties, showcasing a higher flexural modulus of 4431 MPa and an impressive flexural strength of 51.3 MPa. In the tensile tests, the Kaolin filler specimen outperformed those with HGM filler, demonstrating the highest Young's modulus and tensile strength at 2376 MPa and 23.67 MPa, respectively. However, the impact testing results reveal a decrease in energy absorption with increasing HGM content, which is attributed to HGM's high nucleation capacity during crystallization. Composites incorporating 10% HGM (S3) additive within the epoxy resin showcased enhanced impact strength, registering a value of 5.03 kJ/m^2, while the 30% Kaolin filler specimen displayed the lowest impact strength at 3.63 kJ/m^2.

According to the TOPSIS method analysis as shown in Table 8, the ranking of the composites is as follows: S1 (1st rank), S0 (2nd rank), Concrete roof tile (3rd rank), S2 (4th rank), S3 (5th rank). This ranking system provides valuable insights into the overall performance and suitability of each composite, guiding potential applications and material choices.

Table 8. Comparison of results with concrete roof tile using the TOPSIS method.

Specimen	Thermal Conductivity (W/(m·K))	Flexural Modulus (MPa)	Flexural Strength (MPa)	Young's Modulus (MPa)	Tensile Strength (MPa)	Impact Strength (kJ/m²)	Performance Index (P_i)	Price (€)	Rank
Concrete Roof Tile	0.13	7500	5	15,000	7	2	0.68	2	3rd
S0	0.054	3800	38.96	2376	23.67	3.62	0.70	1	2nd
S1	0.005	4431	51.30	1894	19.36	3.65	0.73	28	1st
S2	0.016	2000	31.08	1602	15.62	4.70	0.63	28	4th
S3	0.042	1540	20.24	1064	11.19	5.03	0.55	28	5th

4.2. Comparison with Concrete Roof Tiles

The table below illustrates a comparison between traditional concrete roof tiles and samples incorporating hollow glass microspheres (HGM) and kaolin fillers. It emphasizes the outstanding mechanical and thermal properties of the roof tiles containing HGM and kaolin fillers, surpassing those of concrete roof tiles. The data clearly shows the enhanced strength and superior thermal resistance of the composite material, making it an excellent choice for high-performance roofing materials.

5. Conclusions

In this study, the potential of bamboo epoxy composite materials infused with varying proportions of Hollow Glass Microspheres (HGM) and kaolin additive fillers as thermal insulators for rooftops. Our research focused on understanding the effects of these additives on thermal conductivity, thermal degradation, and the mechanical properties of the composites. The Vacuum Assisted Resin Transfer Molding (VARTM) technique employed in this research shows an efficient method for producing structurally thermal barrier materials. The primary objective was to compare the effects of HGM-filled composites with those containing kaolin fillers, to develop an environmentally friendly and efficient thermal insulating composite material.

Hollow glass microspheres (HGM) and kaolin were used as fillers in this research work to develop bamboo epoxy-reinforced composites with good thermal and mechanical properties. The findings revealed that the addition of HGM filler content influenced the thermal resistance of the bamboo epoxy-reinforced composites because it contains a lot of air within its structure. Air is a poor conductor of heat, and the presence of these air-filled voids within HGM significantly reduces its overall thermal conductivity. HGM fillers reduce density and improve impact resistance, making them suitable for lightweight structural applications. Kaolin fillers in the composite, on the other hand, enhance strength, stiffness, and wear resistance, making composites more durable and rigid.

The research findings represent a noteworthy breakthrough in roofing materials, underscoring the promise of bamboo epoxy composites enriched with

HGM or Kaolin fillers. These composites offer an environmentally responsible alternative compared to traditional concrete roof tiles. Unlike concrete, which involves resource-intensive cement production, these composites harness the sustainability of bamboo and incorporate environmentally friendly fillers. Furthermore, their remarkable thermal insulation properties have the potential to significantly enhance energy efficiency, particularly in regions with extreme climates where heating and cooling costs are substantial concerns. Their lightweight nature also facilitates adaptability to various architectural designs, simplifying transportation and installation. This research points towards a more sustainable, energy-efficient, and adaptable future for roofing materials.

6. Future Scope

This study opens promising avenues for further research on advanced thermal insulating materials, utilizing sustainable and renewable resources like bamboo. Tailoring the proportion of HGM and other additives in the composite matrix could lead to even more optimized performance characteristics. Additionally, exploring the long-term durability and eco-friendliness of these materials under real-world conditions would provide valuable insights for practical applications.

As research in this field advances, these materials have the potential to revolutionize roof tiles by providing sustainable and high-performance alternatives to conventional roof tiles.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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