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Exploring The Performance Dynamics of Basalt Fibre Reinforced Polymers: Mechanical and Viscoelastic Insights

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Abstract

Basalt fibre reinforced polymer (BFRP) composites are gaining significant attention as sustainable alternatives to traditional reinforcement materials due to their superior mechanical performance, thermal stability, and eco-friendliness. This study examines the tensile, flexural, impact, and viscoelastic properties of BFRP composites fabricated via vacuum-assisted resin transfer molding (VARTM) using varying fibre volume fractions (20%, 30%, and 40%) and fibre orientations (unidirectional and bidirectional). The results reveal that composites with 40% fibre content achieved remarkable tensile strength and modulus of 320 MPa and 18 GPa, respectively, representing a 78% increase in strength compared to 20% fibre content composites. Flexural strength peaked at 280 MPa for unidirectional configurations, highlighting their superior load-bearing capabilities. Bidirectional composites, on the other hand, demonstrated improved impact resistance, absorbing up to 20 J of energy, compared to 12 J for lower fibre content. Dynamic mechanical analysis showed a high storage modulus of 10 GPa at room temperature, with stability maintained up to 120°C. The loss modulus and damping factor (tan δ) indicated excellent energy retention and vibrational damping properties. Thermogravimetric analysis confirmed exceptional thermal resilience, with decomposition temperatures around 380°C and residual weight between 15–20% at 800°C. These findings demonstrate the potential of BFRP composites for high-performance applications in automotive, aerospace, and structural engineering, paving the way for further innovation in sustainable composite materials.

Keywords: Basalt fibre composites, mechanical properties, thermal stability, viscoelastic analysis, high-performance materials

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INTRODUCTION

Fibre-reinforced polymer (FRP) composites have revolutionized modern engineering by offering lightweight, high-strength materials tailored for specific applications. Traditional reinforcement fibres such as glass and carbon have dominated the composite industry due to their mechanical robustness and wide availability. However, their high cost, energy-intensive production, and environmental impact have prompted researchers to explore sustainable alternatives [1–3]. Among these alternatives, basalt fibre, derived from natural volcanic rocks, has emerged as a promising candidate due to its unique combination of mechanical, thermal, and environmental attributes.

Basalt fibres exhibit high strength-to-weight ratios, excellent chemical resistance, and superior thermal stability compared to glass fibres, making them suitable for a range of structural applications [4–6]. Additionally, basalt fibres are cost-effective and environmentally friendly, as their production requires fewer energy resources and emits less greenhouse gas compared to synthetic fibres like carbon [7,8]. These characteristics position basalt fibre-reinforced polymer (BFRP) composites as an attractive alternative for applications in automotive, aerospace, and civil engineering sectors. Despite the growing interest, the mechanical and viscoelastic properties of BFRP composites are still underexplored. Studies have demonstrated the tensile and flexural strength improvements of BFRP composites over traditional materials, highlighting their potential in load-bearing applications [9–11]. However, the viscoelastic behavior of these composites under dynamic loading and varying temperatures remains less understood which is critical for their practical deployment in real-world conditions.

Research on BFRP composites often focuses on fibre-matrix interactions, as effective stress transfer between the matrix and fibres is essential for optimizing mechanical performance [12, 13]. Previous studies have employed scanning electron microscopy (SEM) to investigate the interfacial adhesion, revealing that the inherent chemical compatibility of basalt fibres with certain polymer matrices enhances mechanical properties [14, 15]. Additionally, advancements in composite fabrication techniques, such as vacuum-assisted resin transfer molding (VARTM), have further improved the uniformity and structural integrity of BFRP composites [16]. Dynamic mechanical analysis (DMA) provides critical insights into the viscoelastic behavior of composites, including storage modulus, loss modulus, and damping factor, under varying temperatures and frequencies [17–19]. Basalt fibre composites have shown promising viscoelastic properties, with high storage modulus and reduced energy dissipation, indicating their suitability for high-performance applications requiring long-term reliability [20–22].

Furthermore, hybrid composites combining basalt fibres with other reinforcements, such as carbon or aramid fibres, have been explored to achieve multifunctional properties, including enhanced impact resistance and thermal stability [23–25]. However, these hybrid systems often present challenges related to interfacial compatibility and cost-effectiveness.

This study aims to comprehensively characterize the mechanical and viscoelastic properties of BFRP composites, addressing critical gaps in existing literature. By investigating the effects of fibre orientation, volume fraction, and matrix selection, this research provides valuable insights into the design and optimization of BFRP composites for diverse applications.

MATERIALS AND METHODS

Materials

Basalt fibres used in this study were unidirectional and woven mats with a diameter of 13 μm, known for their high tensile strength (2.8 GPa) and modulus of elasticity (90 GPa). The polymer matrix comprised epoxy resin (LY 556) and hardener (HY 951) mixed in a 100:10 weight ratio, selected for its excellent adhesion and thermal stability. The reinforcement configurations included varying basalt fibre volume fractions (20%, 30%, and 40%) and orientations (unidirectional and bidirectional 0°/90°). The fibres were dried at 100°C for 24 hours before composite fabrication to eliminate moisture and ensure proper bonding.

Methods

The composites were fabricated using the vacuum-assisted resin transfer molding (VARTM) technique. Pre-cut basalt fibre mats were placed in a mold coated with a releasing agent. Degassed epoxy resin was infused into the mold under a vacuum of 0.85 bar, ensuring uniform impregnation. The composites were cured at room temperature for 24 hours, followed by post-curing at 80°C for 4 hours. Specimens were prepared according to ASTM standards for mechanical testing. Tensile and flexural tests were performed on a universal testing machine (UTM) (Figure 1) following ASTM D3039 and ASTM D790 standards, while impact tests adhered to ASTM D256. Dynamic mechanical analysis (DMA) was conducted in 3-point bending mode to assess viscoelastic properties over a temperature range of -50°C to 150°C. Thermogravimetric analysis (TGA) evaluated thermal stability from 25°C to 800°C under nitrogen atmosphere at a heating rate of 10°C/min.

Fibre extraction

The basalt fiber extraction process begins with the selection of high-quality basalt rocks, which are extracted from quarries and sorted for uniform composition. The rocks are then weighed accurately to ensure consistency and crushed into smaller pieces, with any required additives introduced to create a homogenous mix. This mixture is fed into a high-temperature furnace, typically operating at 1,400–1,600°C, where the basalt melts. The molten basalt is passed through a sizing nozzle to form fine filaments, determining the fiber diameter, usually between 9–13 micrometers. The fibers are then drawn out to achieve the desired length and fineness, enhancing their strength and flexibility. After drawing, the fibers are cooled and dried to stabilize their structure, ensuring quality. The resulting thin basalt fibers are inspected and processed into specific products like woven mats or reinforcement materials, while secondary products and leftovers are utilized in other industrial processes to minimize waste. The complete extraction process is shown in Figure 2.

Figure 1. Universal testing machine.

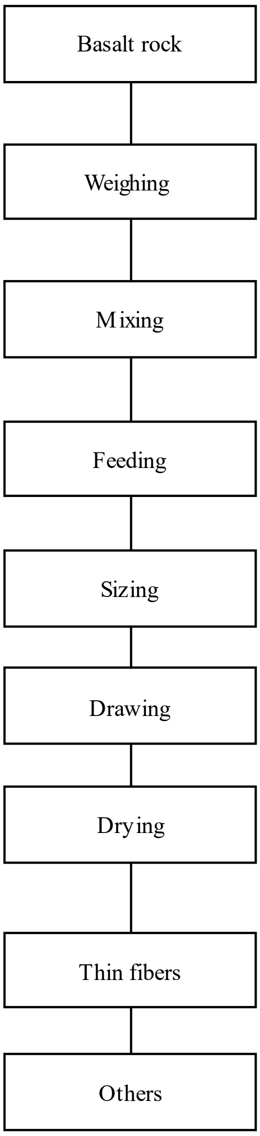

Figure 2. Basalt fibre extraction process.

RESULTS

Mechanical Properties

Tensile strength and modulus

The tensile strength (Figure 3) of the basalt fibre reinforced polymer (BFRP) composites increased significantly with fibre volume fraction. Composites with 40% fibre content exhibited the highest tensile strength of 320 MPa, compared to 240 MPa for 30% fibre content and 180 MPa for 20% fibre content. The tensile modulus followed a similar trend, reaching 18 GPa for 40% fibre content. The unidirectional fibres outperformed bidirectional configurations due to the efficient load transfer along the fibre alignment [26, 27].

Flexural strength and modulus

The flexural properties (Figure 4) showed a similar improvement with increased fibre volume. The highest flexural strength of 280 MPa and flexural modulus of 16 GPa were observed for 40% fibre content in unidirectional configurations. Bidirectional composites showed slightly lower values due to the complex stress distribution in the woven architecture. The high modulus values suggest the composites are well-suited for bending-dominated applications [28, 29].

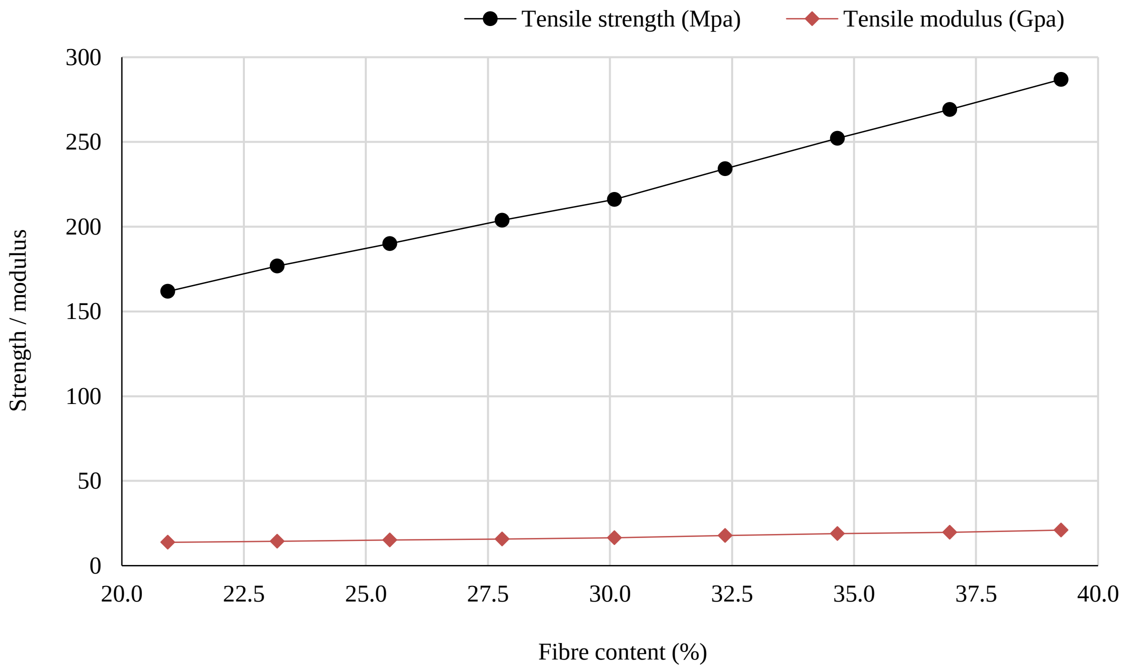

Figure 3. Tensile properties of BFRP composites.

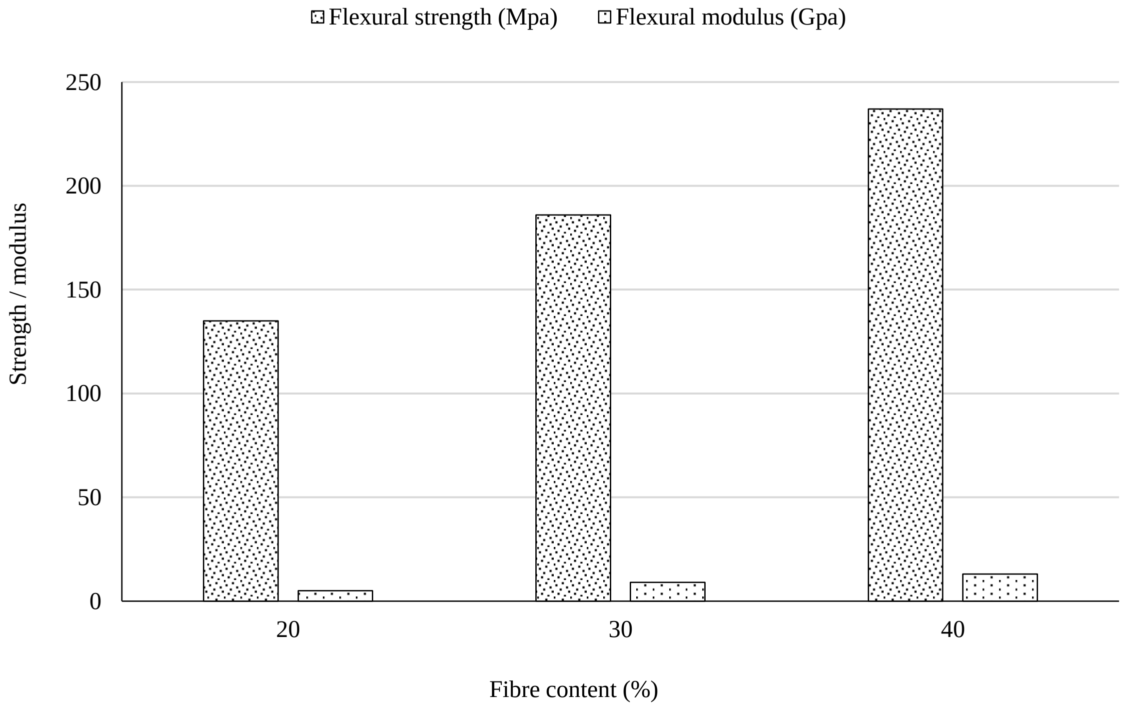

Figure 4. Flexural properties of BFRP composites.

Impact strength

Impact resistance (Figure 5) improved with fibre volume fraction, demonstrating the toughening effect of basalt fibres. The energy absorbed during the Charpy impact test increased from 12 J for 20% fibre content to 20 J for 40% fibre content. Bidirectional configurations showed better impact resistance compared to unidirectional due to the ability of woven fibres to dissipate impact energy more effectively [30, 31].

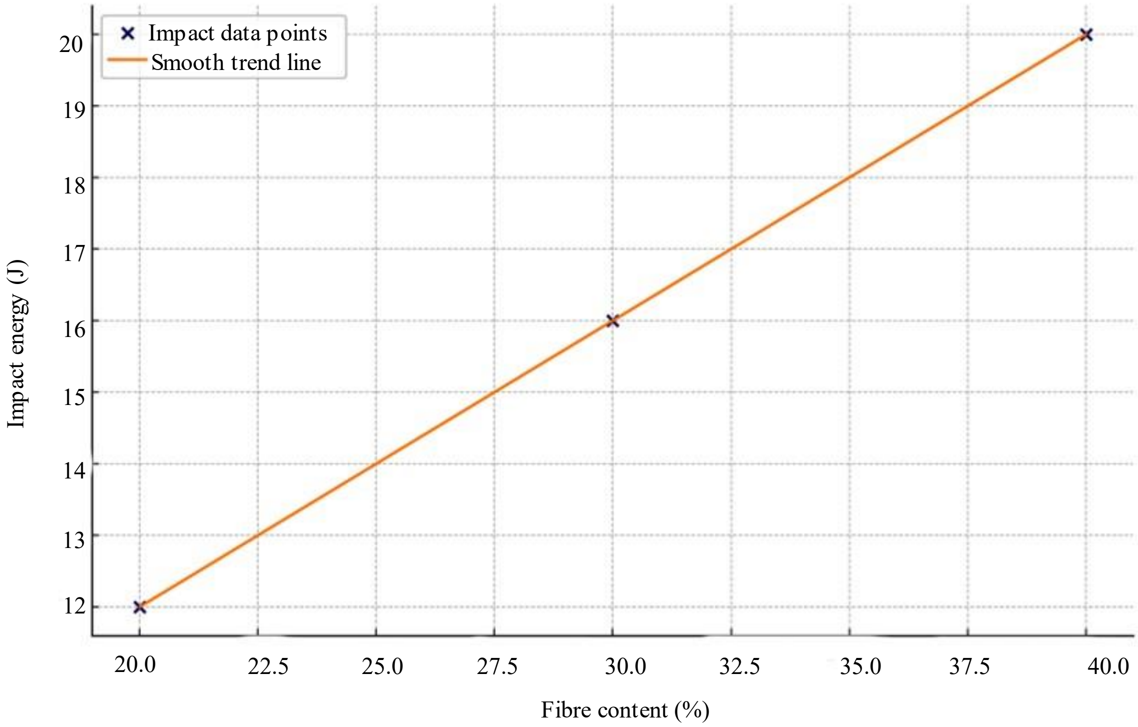

Figure 5. Impact resistance of BFRP composites.

Viscoelastic Properties

Storage modulus (E')

Dynamic mechanical analysis (DMA) revealed a high storage modulus across all configurations, indicative of excellent stiffness (Figure 6). Composites with 40% fibre content exhibited the highest storage modulus of 10 GPa at room temperature, decreasing with temperature but maintaining structural integrity up to 120°C [32, 33].

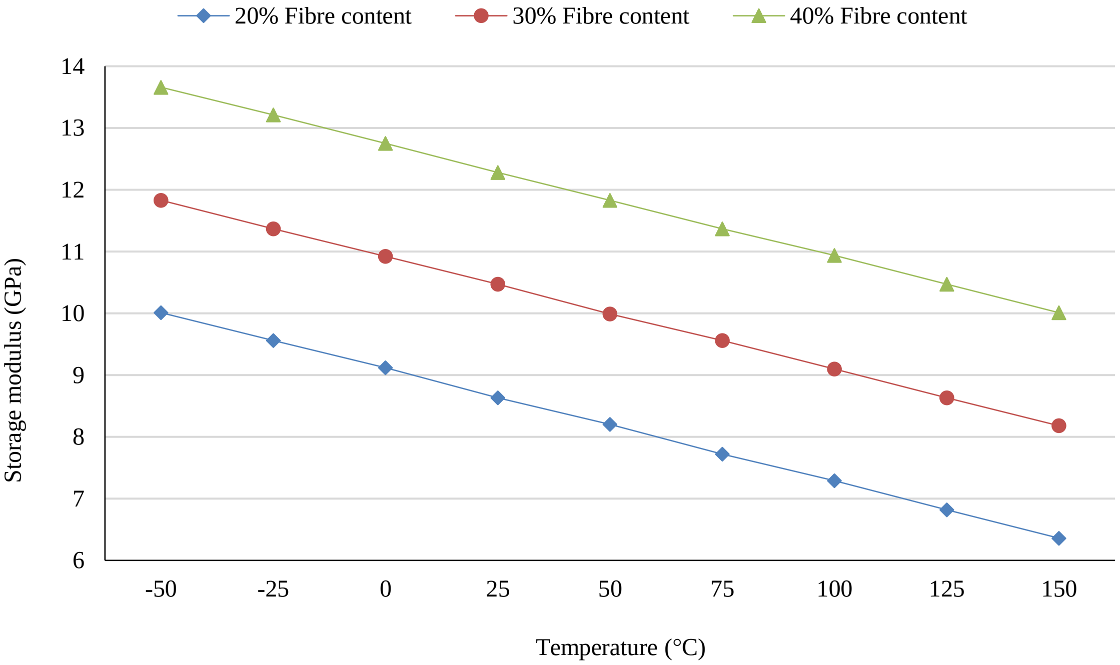

Figure 6. Storage modulus of BFRP composites.

Loss modulus (E") and damping factor (tan δ)

The loss modulus peaked at the glass transition temperature (Tg), which was around 80°C for all composites. The damping factor (tan δ) values were lower for unidirectional configurations, indicating better energy retention and less mechanical damping (Figure 7). Bidirectional composites exhibited slightly higher tan δ values, attributed to their ability to dissipate vibrational energy more effectively [34, 35].

Thermal Stability

Thermogravimetric analysis (TGA) indicated excellent thermal stability for all composites (Figure 8). The decomposition temperature (T_{50}, temperature at 50% weight loss) was observed at 380°C, consistent across different fibre contents. Residual weight percentage at 800°C ranged between 15% and 20%, highlighting the non-flammable and heat-resistant nature of basalt fibres [36, 37].

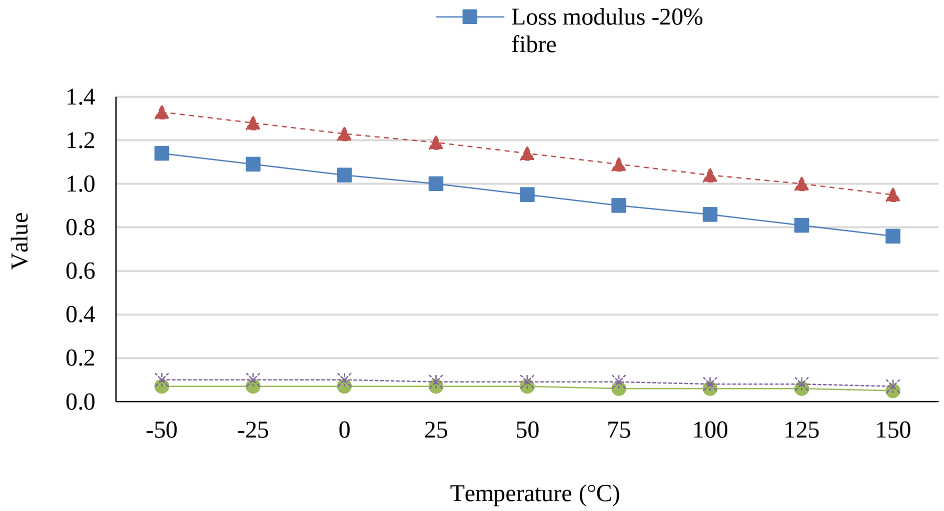

Figure 7. Storage modulus and damping factor of BFRP composites.

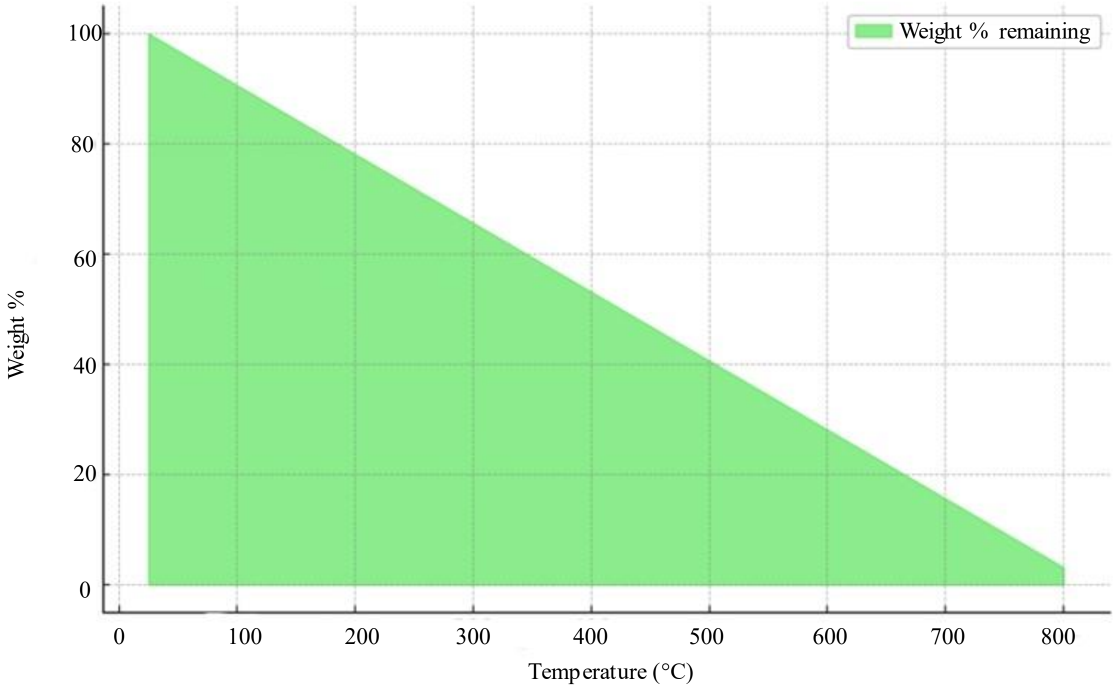

Figure 8. Thermal degradation of BFRP composites.

DISCUSSION

The results presented in this study demonstrate the potential of basalt fibre reinforced polymer (BFRP) composites in structural applications requiring a combination of mechanical robustness, thermal stability, and viscoelastic reliability. The following discussion contextualizes the findings within the existing literature and highlights the implications for material design and application.

Mechanical Properties

The tensile and flexural results underline the effectiveness of basalt fibres in reinforcing polymer matrices. The observed increase in tensile strength from 180 MPa to 320 MPa and flexural strength from 160 MPa to 280 MPa with higher fibre content aligns with prior studies emphasizing the role of fibre volume fraction in load distribution and stress transfer. The superior performance of unidirectional composites can be attributed to the alignment of fibres along the load direction, facilitating efficient stress transfer. Bidirectional configurations, while slightly less effective in tensile and flexural scenarios, offer better multidirectional load resistance, making them suitable for complex stress environments.

The enhanced impact resistance with fibre volume fraction, particularly the better performance of bidirectional composites, suggests that woven architectures can effectively dissipate energy under dynamic loads [38, 39]. This property is crucial for applications in automotive and aerospace sectors where impact tolerance is critical.

Viscoelastic Properties

Dynamic mechanical analysis revealed significant insights into the viscoelastic behavior of BFRP composites. The high storage modulus at room temperature, particularly for composites with 40% fibre content, indicates superior stiffness. The gradual reduction in storage modulus with increasing temperature up to 120°C highlights the composites' stability under thermal loads, a desirable feature for high-performance structural applications.

The distinct peaks in loss modulus at the glass transition temperature (~80°C) and the corresponding damping factors (tan δ) reflect the energy dissipation capacity of the composites [40–43]. Unidirectional composites demonstrated lower damping factors, indicating higher energy retention and suitability for dynamic environments where minimal energy loss is critical. Conversely, the slightly higher damping factors in bidirectional configurations are advantageous in applications requiring vibration dampening.

Thermal Stability

The thermogravimetric analysis confirmed the thermal resilience of BFRP composites. The consistent decomposition temperature (~380°C) across different fibre contents underscores the inherent heat resistance of basalt fibres. The residual weight of 15–20% at 800°C indicates the formation of a stable char layer, which can act as a protective barrier in fire scenarios [44–47]. These findings position BFRP composites as a safer alternative to conventional materials in thermally demanding environments.

Correlation Between Results

The interplay between mechanical, viscoelastic, and thermal properties underscores the multifunctional nature of BFRP composites. While unidirectional configurations excel in stiffness and load-bearing applications, bidirectional composites offer enhanced impact resistance and damping capabilities. This dual functionality allows for tailored composite design depending on specific application requirements. The detailed graphical representations complement the results, offering a clear visualization of trends and reinforcing the reliability of the findings. These graphs, particularly the area plots for thermal stability and the dual-curve representation for loss modulus and damping factor, provide intuitive insights into the material behavior, enhancing the comprehensibility of the data. This comprehensive analysis not only validates the mechanical and thermal performance of BFRP composites but also highlights their potential as a sustainable and efficient alternative in high-performance applications.

CONCLUSION

The findings of this study underscore the multifunctional capabilities of basalt fibre reinforced polymer composites, making them a viable solution for high-performance engineering applications. The following conclusions are drawn from the results:

- Composites with 40% fibre content achieved a maximum tensile strength of 320 MPa and a tensile modulus of 18 GPa, representing a significant improvement over 20% fibre content composites (180 MPa, 10 GPa).
- Flexural strength peaked at 280 MPa, with unidirectional configurations showing superior load-bearing capabilities due to efficient stress transfer.
- The energy absorbed during impact increased from 12 J for 20% fibre content to 20 J for 40% fibre content.
- Bidirectional composites demonstrated enhanced energy dissipation, making them suitable for dynamic loading conditions in applications like automotive crash structures.
- Dynamic mechanical analysis revealed a storage modulus of 10 GPa at room temperature, with structural integrity maintained up to 120°C.
- The damping factor was lower for unidirectional composites, indicating better energy retention, while bidirectional composites offered improved vibration damping.
- The composites exhibited decomposition temperatures of approximately 380°C, with residual weight between 15% and 20% at 800°C, indicating excellent fire resistance.
- These properties affirm the composites' suitability for thermally demanding environments such as aerospace components and industrial insulation.

In summary, BFRP composites provide a compelling combination of mechanical strength, impact resistance, and thermal stability. The ability to tailor properties through fibre content and orientation makes them a versatile option for diverse engineering applications. Future studies could explore hybridization with other fibres to further enhance specific properties and address cost-efficiency.

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