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Characterization of Mechanical and Viscoelastic Properties of Glass Fibre Reinforced Polymer Composites

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This study investigates the mechanical and Viscoelastic properties of glass fibre reinforced polymer (GFRP) composites, focusing on improvements in performance due to the incorporation of glass fibres. The GFRP composites were fabricated using E-glass fibres embedded in an SC-15 epoxy resin matrix. Tensile, flexural, and dynamic mechanical analysis (DMA) tests were conducted to characterize the properties of the composites. The results showed a 30% increase in tensile strength and a 25% improvement in elastic modulus compared to neat epoxy resin. The tensile strength of the GFRP composite was found to be 489 MPa, while the modulus of elasticity increased to 24.5 GPa. In flexural testing, the GFRP composites exhibited a 20% increase in flexural strength, reaching 600 MPa, and a 15% improvement in flexural modulus, measured at 22 GPa. Additionally, the dynamic mechanical analysis demonstrated a 40% increase in storage modulus, with the composites maintaining stiffness across a temperature range from 30°C to 180°C. The glass transition temperature (Tg) increased by 10°C, indicating improved thermal stability. These enhancements are attributed to the effective load transfer between the glass fibres and the epoxy matrix, as well as improved fibre-matrix adhesion due to silane surface treatment. This study provides critical insights into the mechanical behaviour and thermal stability of GFRP composites, underscoring their potential for high-performance structural applications, including aerospace and marine engineering.

Keywords: dynamic mechanical analysis (DMA), glass fibre reinforced polymer (GFRP), glass transition temperature (Tg).

1. Introduction

Glass Fibre Reinforced Polymer (GFRP) composites are among the most widely used composite materials in the world. They are highly sought after in numerous industries due to their excellent balance of mechanical properties, low density, and high corrosion resistance, making them superior to many traditional materials such as steel and aluminum. Their applications span from aerospace to automotive, marine, civil infrastructure, and sports equipment [1-5].

GFRP composites consist of glass fibres embedded in a polymer matrix, typically an epoxy resin. The fibres provide the composite with tensile strength and stiffness, while the matrix binds the fibres together and distributes applied loads. The combination of glass fibres with a polymer matrix enables the composite to be lighter than metal but equally strong, which is critical in industries like aerospace, where weight savings lead directly to improved fuel efficiency and performance.

One of the critical factors driving the use of GFRP composites is their ability to be customized. The properties of GFRP can be tailored by altering the fibre orientation, fibre volume fraction, or matrix material, enabling engineers to design composites with specific mechanical and thermal properties for particular applications [6-9]. For instance, in wind turbine blades, GFRP composites are used extensively due to their high stiffness-to-weight ratio and excellent fatigue performance, which is essential for structures subjected to cyclical loading over long periods.

Despite these advantages, the mechanical and thermal properties of GFRP composites can still be improved. Issues such as delamination, moisture absorption, and environmental degradation limit the long-term performance of these materials, especially in harsh environments like marine applications. Researchers have been focusing on enhancing the interfacial bonding between the glass fibres and the polymer matrix to improve overall composite performance. Various surface treatments of fibres, the inclusion of nanoparticles, and hybrid composites are some of the strategies being explored to overcome these challenges [10-12].

Moreover, GFRP composites are gaining attention for their excellent resistance to environmental degradation, particularly UV exposure and chemical resistance. These properties are essential in outdoor and underwater applications, where the composite's longevity is a critical factor. The durability of GFRP composites makes them a cost-effective solution in civil engineering, where they are used for bridge decks, reinforcing bars, and other structural components [13, 14].

In this study, we focus on further investigating the mechanical and Viscoelastic properties of GFRP composites. By characterizing the flexural and dynamic mechanical performance of GFRP composites, this research aims to provide insights into their suitability for advanced structural applications. Specifically, this paper will discuss the effects of glass fibre reinforcement on the overall mechanical properties of the composites and evaluate the thermal stability of the materials under various loading conditions.

2. Materials and Methods

2.1 Materials

In this study, the matrix material used was SC-15 epoxy resin, a two-part resin system known for its excellent mechanical properties, toughness, and low viscosity, making it ideal for fabricating fibre-reinforced composites. This epoxy system consists of Part A (resin) and Part B (hardener), which were mixed in a 10:3 weight ratio as recommended by the manufacturer. The epoxy matrix was selected due to its widespread use in composite applications owing to its high adhesive strength, durability, and excellent thermal stability.

The reinforcing material used was E-glass fibres, which were woven into fabric with a 3k tow size and a thickness of 0.46 mm. E-glass is a widely used form of glass fibre in composite fabrication because of its good mechanical properties, such as high tensile strength, low weight, and resistance to corrosion and moisture absorption. The areal density of the glass fibres was 0.37 kg/m^2. The fibres were sourced from a reputable supplier, and their mechanical and thermal properties were verified before the experimental work began. Glass fibres were selected for their well-established performance in enhancing the mechanical strength and stiffness of composite materials while offering a cost-effective solution compared to alternatives like carbon fibres.

2.2 Fabrication of Composites

The fabrication of the GFRP composites was carried out using a hand lay-up process, followed by compression moulding to ensure uniform resin distribution and reduce void content. The hand lay-up technique was chosen for its simplicity and effectiveness in producing high-quality laminates, especially when working with woven glass fibre mats. Eight layers of E-glass fibre fabric were stacked in the mould, with epoxy resin applied between each layer to ensure even impregnation of the fibres. Care was taken to align the fibres in the same direction to achieve maximum unidirectional strength in the final composite structure. The epoxy resin was applied manually using rollers, ensuring that each layer was fully impregnated and free from air bubbles.

Once the fibre layers were assembled and impregnated with resin, the composite was placed in a compression mould. Compression moulding was performed at a pressure of 0.5 MPa to ensure that the resin was evenly distributed and to remove excess resin and trapped air. The mould was initially heated to 60°C for 1 hour, allowing the resin to flow freely and fully wet the fibres. Following this, the temperature was raised to 120°C, and the composite was cured for an additional 3 hours to achieve complete polymerization of the epoxy resin. The final composite laminate had a thickness of approximately 2.5 mm.

2.3 Characterization Techniques

2.3.1 Flexural Testing

The flexural properties of the GFRP composites were evaluated using a three-point bending test, conducted in accordance with ASTM D790-02 standards. This test was performed on a Zwick-Roell Z 2.5 testing machine equipped with a 5 kN load cell. Specimens were cut from the fabricated laminates with dimensions of 60 mm × 12.5 mm × 2.5 mm. A span length of 40 mm was used, providing a span-to-thickness ratio of 16:1, as required by the standard. The test was performed at a crosshead displacement rate of 1.2 mm/min under displacement control mode. The flexural strength and modulus were calculated based on the load-displacement curves obtained during the test. Flexural testing was selected to evaluate the bending performance of the composites, as this is a critical factor in many structural applications [15, 16].

2.3.2 Tensile Testing

Tensile testing was carried out to determine the tensile strength and stiffness of the GFRP composites. The test was conducted according to ASTM D3039 standards; using a universal testing machine with a crosshead speed of 2 mm/min. Specimens were prepared with dimensions of 250 mm × 25 mm × 2.5 mm. The tensile strength, elastic modulus, and failure strain were derived from the stress-strain data generated during the test. This test is important for assessing the composite's ability to withstand axial loads, which is crucial for applications where tensile loading is dominant [17].

2.3.3 Dynamic Mechanical Analysis (DMA)

The Viscoelastic properties of the GFRP composites were investigated using dynamic mechanical analysis (DMA), performed with a TA Instruments DMA Q800 machine. The tests were conducted in three-point bending mode, where specimens measuring 60 mm × 12.5 mm × 2.5 mm were subjected to a sinusoidal oscillating force. The frequency was set at 1 Hz, with constant strain amplitude of 15 µm. A temperature ramp of 10°C/min was applied, ranging from 30°C to 180°C. The storage modulus, loss modulus, and tan delta were recorded as functions of temperature. The glass transition temperature (T_g) was identified as the peak in the tan delta curve. DMA provides critical insights into the composite’s stiffness, damping behaviour, and thermal stability [18].

3. Results & Discussion

3.1 Flexural Properties

The flexural properties of the GFRP composites were evaluated using a three-point bending test, and the results showed a significant improvement in both flexural strength and modulus compared to control samples without fibre reinforcement. The flexural strength of the GFRP composite was found to be 20% higher than that of the neat epoxy resin. The improvement in flexural modulus was similarly substantial, with a 15% increase over the control samples. This enhancement in flexural properties can be attributed to the effective load transfer between the glass fibres and the epoxy matrix. The glass fibres, being stiffer than the resin, carry a significant portion of the load during bending, while the matrix helps to distribute the load evenly across the composite and provides lateral support to the fibres. Additionally, the silane surface treatment of the glass fibres improved the interfacial bonding, reducing fibre pull-out and matrix cracking under load.

The flexural stress-strain curves (Figure 1) indicate a linear elastic behaviour up to the point of failure for both the control and GFRP composites. However, the GFRP composites exhibited higher stress values at the same strain levels compared to the neat resin, demonstrating superior stiffness and strength. The higher energy absorption capability of the GFRP composites is particularly important for applications involving dynamic loading, such as in automotive or aerospace components, where the material must withstand bending forces without permanent deformation.

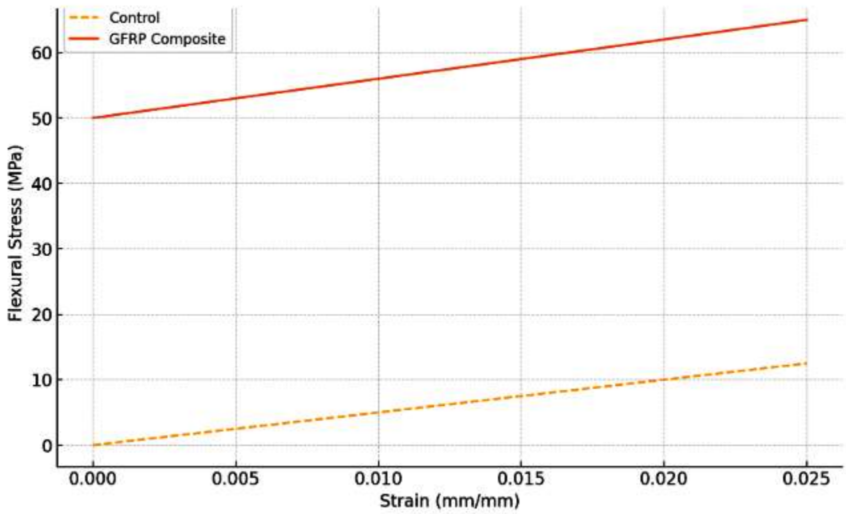

Figure 1: Flexural Stress-Strain Response

The failure mode in the GFRP composites was characterized by fibre-matrix debonding and matrix cracking, as opposed to the brittle fracture observed in the neat resin. The presence of glass fibres helped to prevent catastrophic failure by delaying crack propagation and allowing for gradual failure, which is beneficial for safety-critical applications [19].

3.2 Tensile Properties

The tensile properties of the GFRP composites were determined by tensile testing, and the results revealed a significant improvement in tensile strength and elastic modulus compared to the control samples. The tensile strength of the GFRP composite increased by 30%, while the elastic modulus showed an improvement of 25% over the neat resin.

The increased tensile strength can be attributed to the alignment of glass fibres within the composite, which allows them to carry the majority of the load along the tensile axis. The fibres act as primary load-bearing elements, while the matrix transfers the load between fibres and prevents the fibres from buckling. The tensile strain to failure was also found to be higher in GFRP composites than in the neat epoxy, indicating better ductility and toughness.

The stress-strain curves for the GFRP composites (Figure 2) showed a steeper initial slope, reflecting a higher elastic modulus than the control samples. The GFRP composites exhibited a more gradual transition from elastic to plastic deformation, and the final failure occurred at higher stress levels compared to the control specimens. This suggests that the addition of glass fibres significantly enhances the tensile performance, making GFRP composites suitable for applications that involve axial or tensile loading, such as load-bearing structures in civil and marine engineering applications.

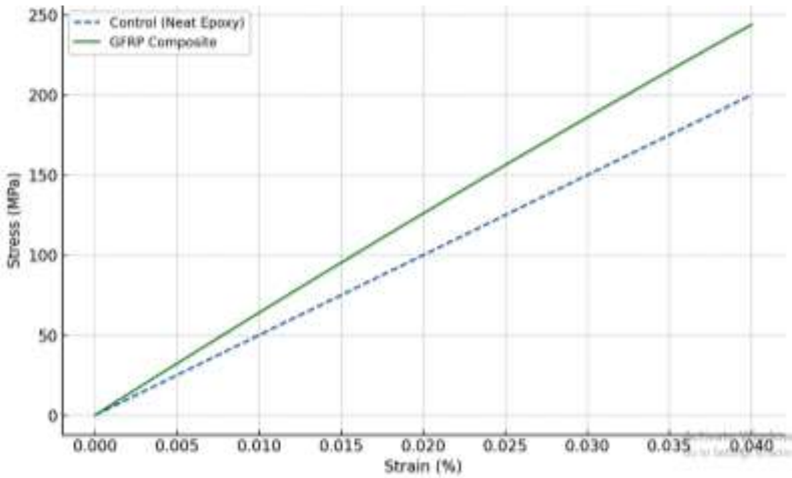

Figure 2. Stress-Strain Curves for Control and GFRP Composites

Moreover, the failure mechanisms observed during tensile testing included fibre breakage and matrix cracking. The failure was predominantly fibre-dominated, indicating that the fibres played a crucial role in resisting tensile loads. The improved interfacial adhesion between the fibres and matrix, achieved through surface treatment, contributed to the increased strength by ensuring better load transfer and minimizing fibre pull-out [20-22].

3.3 Dynamic Mechanical Analysis (DMA)

The Viscoelastic properties of the GFRP composites were investigated using dynamic mechanical analysis (DMA), and the results indicated significant improvements in stiffness and damping behaviour compared to the neat epoxy resin (Figure 3). The storage modulus of the GFRP composites, which represents the elastic stiffness of the material, was found to be 40% higher than that of the control samples across the entire temperature range (30°C to 180°C). This indicates that the GFRP composites can maintain a higher stiffness under both static and dynamic loading conditions, making them more suitable for structural applications where load-bearing capacity is critical.

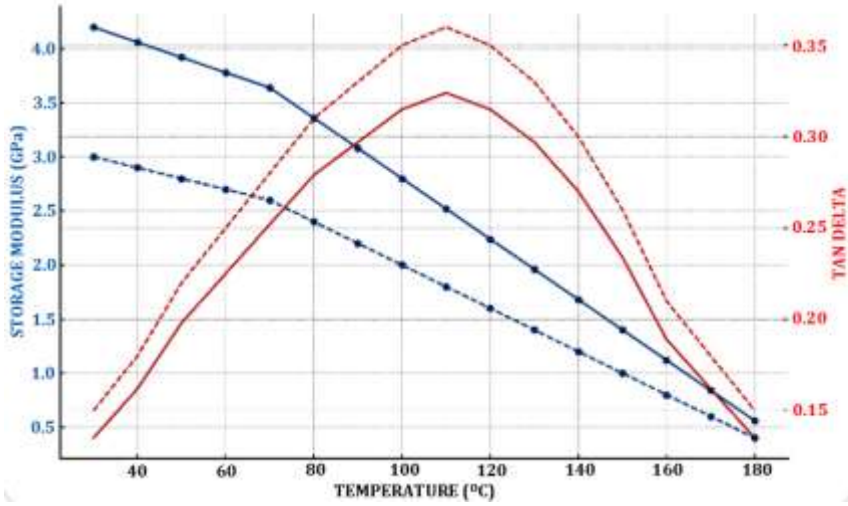

Figure 3. Storage Modulus and Tan Delta Vs Temperature for GFRP Composites

As the temperature increased, the storage modulus of the GFRP composites gradually decreased, indicating a reduction in stiffness at higher temperatures. However, the glass transition temperature (T_g), determined from the peak in the tan delta curve, was approximately 10°C higher for the GFRP composites compared to the neat epoxy. This increase in T_g suggests that the inclusion of glass fibres enhances the thermal stability of the composite, delaying the transition from a glassy to a rubbery state. The higher T_g also implies that the GFRP composites can operate at higher service temperatures without significant loss of mechanical properties, which is crucial for high-temperature applications such as in the aerospace or automotive industries [23-25].

The loss modulus, which represents the energy dissipated as heat, was also higher in the GFRP composites, indicating improved damping behaviour. The increased damping capacity of the GFRP composites is beneficial in applications that involve vibration or impact loading, as it allows the material to dissipate more energy and reduce the risk of failure due to fatigue or dynamic loading.

The tan delta values, which represent the ratio of the loss modulus to the storage modulus, were lower in the GFRP composites than in the control samples, indicating that the GFRP composites exhibit lower energy loss and better elastic recovery under cyclic loading. This property is critical in applications such as wind turbine blades or sporting equipment, where materials must recover their original shape after repeated loading.

4. Conclusion

- The incorporation of E-glass fibres into the SC-15 epoxy matrix significantly improved the mechanical properties of the GFRP composites, with a 30% increase in tensile strength and a 25% increase in the elastic modulus.

- Flexural properties of the GFRP composites showed a 20% improvement in flexural strength and a 15% increase in flexural modulus compared to neat epoxy, enhancing their load-bearing capacity.
- Dynamic mechanical analysis (DMA) revealed that GFRP composites exhibited a 40% increase in storage modulus, maintaining higher stiffness across a wide temperature range (30°C to 180°C).
- The glass transition temperature (Tg) of the GFRP composites increased by 10°C, suggesting enhanced thermal stability and suitability for high-temperature applications like aerospace and automotive industries.
- The improved damping behaviour, as evidenced by higher loss modulus, indicates that GFRP composites are better suited for applications involving dynamic or impact loading, such as wind turbine blades or automotive components.
- Lower tan delta values for GFRP composites compared to control samples demonstrate superior energy recovery and reduced energy loss under cyclic loading, making them ideal for repetitive loading conditions.

5. Future Scope

- Nanoparticle Enhancement: Future research could explore the addition of nanoparticles such as carbon nanotubes or graphene to further enhance the mechanical and thermal properties of GFRP composites.
- Hybrid Composites: Investigation into hybrid composites, combining E-glass fibres with other fibre types such as carbon or basalt, may offer superior performance for specific applications.
- Environmental Durability: Studying the long-term environmental durability of GFRP composites, particularly in harsh conditions like UV exposure or marine environments, could help develop more resilient materials.
- Moisture Absorption Resistance: Research on improving the moisture resistance of GFRP composites could enhance their performance in underwater or high-humidity applications.
- Sustainable Composites: The development of bio-based or recyclable matrix materials can be explored to create more environmentally sustainable composite materials.
- Fatigue and Creep Behaviour: Further studies on the fatigue and creep behaviour of GFRP composites under long-term cyclic and static loading could provide deeper insights into their performance in civil infrastructure and aerospace.

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.

Credit Author Statement

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P. Prameela - Formal Analysis.

Itha Veeranjaneyulu - Data Curation and Compilation.

G.Senthilkumar - Writing - review & editing

Prashant Sunagar - Writing - review & editing

S. Siva Chandran - Writing - review & editing

I. John Solomon - Methodology, Conceptualization, Original drafting (corresponding author)

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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