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Mechanical, Thermal, and Thermogravimetric Characterization of Pebble Natural Filler-Reinforced Epoxy Composites Fabricated by the Hand Lay-Up Technique

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Abstract

The mechanical, dynamic, and thermal properties of an epoxy-based composite reinforced with pebble fillers and carbon fibres were investigated. Experimental evaluations were conducted to determine tensile, flexural, impact, and interlaminar shear strengths. The study compares the mechanical behaviour of carbon fibre-reinforced composites fabricated using conventional epoxy (NE) as the matrix material. Comparative analyses were performed on composites containing 15 wt% and 20 wt% carbon fibre. In addition, compressive strength and damping ratio were assessed to provide a more comprehensive evaluation of composite performance. The epoxy resin was reinforced with unidirectionally aligned carbon fibres at 15 wt% and 20 wt%, along with pebble fillers, to produce hybrid composite specimens. The primary objective of this research was to gain a deeper understanding of the interfacial bonding mechanisms between the damping materials and the epoxy matrix, thereby improving the overall bonding performance. The findings contribute to the selection of suitable materials for engineering applications and support the design and development of high-performance composite structures.

Introduction

Among the different types of matrix materials, polymer matrices are the most widely used because of their cost-effectiveness, ease of fabricating complex components with minimal tooling requirements, and favourable mechanical properties at room temperature [1]. Over the past few decades, composite materials have become increasingly important in the manufacture of machine tool structures due to their superior vibration-damping capabilities [2,3]. Compared with conventional materials such as steel and concrete, polymer composites offer significant advantages, including lower weight, a higher strength-to-weight ratio, and improved resistance to fracture. Like all engineered materials, polymer composites dissipate energy when subjected to cyclic loading. Their outstanding stiffness-to-weight ratio makes polymer matrix composites particularly suitable for applications where weight reduction is a critical design consideration [4–6].

Recent advancements in material development, manufacturing techniques, and analytical models have addressed many engineering challenges. Nevertheless, further research is still needed to evaluate and identify the most effective combinations of materials and process parameters that can optimize the performance of bonded joints [7].

1. Experimental Methods

2. 1.1. Fabrication

The epoxy resin (Araldite) used in this study was procured from Petro Araldite Pvt. Ltd., Chennai, while T300 carbon fibre (CF) was obtained from Sakthi Industries, Chennai, and used as the reinforcing material. River sand was incorporated as a micro-filler to improve the interfacial bonding between the epoxy matrix and pebble stone filler. The epoxy resin components were blended with unidirectionally aligned carbon fibre mats at reinforcement levels of 15 wt% and 20 wt% using a mild steel mould. Pebble filler was dispersed into the epoxy resin through continuous mechanical stirring at a constant speed of 500 rpm for 24 hours to ensure a homogeneous mixture before fabrication. The sample designations for the various epoxy composite formulations are presented in Table 1.

1.2. Testing

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Composite specimens were fabricated with dimensions of 200 × 30 × 5 mm, 130 × 30 × 5 mm, and 63.5 × 12.7 × 3.2 mm, depending on the specific test requirements. The compressive strength of the unidirectionally reinforced composites was evaluated in accordance with ASTM C579–01. For each test condition, five specimens were tested, and the average value was reported. Thermal stability and degradation behaviour were investigated using thermogravimetric analysis (TGA) with a PerkinElmer Pyris 7 thermogravimetric analyser. Approximately 10 mg of each sample was heated in an air atmosphere from room temperature to 900 °C at a heating rate of 5 °C/min to determine the onset of decomposition, percentage of mass loss, and maximum decomposition temperature. Dynamic Mechanical Analysis (DMA) was performed to evaluate the dynamic mechanical properties of the fabricated composites.

3. Results and Discussion

3.1. Mechanical Properties. Epoxy composites with various fibre contents were compared to plain epoxy in terms of tensile, flexural, impact, and interlaminar shear stress characteristics (NE). The mechanical characteristics of the tested materials are shown in Figure 1(a) and Figure 1(b). The addition of a pebble to the carbon fibre increases the strength of all composites in general. The tensile strength of neat epoxy resin was increased from 78 MPa (NE) to 372 MPa (CP15a) and 374 MPa (CP15b) with the addition of a filler and fibre. In the same fibre and filler ratio, flexural, impact, and interlaminar shear stress all improved. According to this study, the mechanical properties of fibre- reinforced composites are influenced not only by the fibre content but also by the pebble filler, which aids in stress transfer to the matrix [14].

The addition of filler raised the tensile strength of the epoxy composites by up to 15% in both matrixes. The filler results in increased interfacial addition and as a result, more stress transfer fibres and fillers during tensile testing. It is worth noting that the effect of pebble filler on the flexural strength of epoxy composites greatly improves the stiffness of the composites. When flexural strength of both sets of carbon fibre loading 15 wt% and 20 wt% with different

3.2. Compressive Test and Damping Ratio Analysis. Figure 2 depicts representative behaviours of the four composite materials. The addition of a pebble filler to the matrix improves the properties of carbon fibre/epoxy matrix composites, albeit the degree of improvement is dependent on factors including filler particle concentration and dis- persion. According to the compressive strength values of composites CP15a and CP15b, it is determined that 15 percent pebble filler provides greater strength than 20% pebble filler.

CP15a and CP15b have maximum compressive strength values of 60% and 61% higher than neat epoxy samples. For the abovementioned composites, considering the scattering and failure, describing the nonlinear behaviour and the shear strength values are not very affected. Because shear strength can induce a drop in compressive strength in the fibre composite, the pebble filler reduced compressive strength by 20%. Normally, the composite with lesser weight proportion of resin shows better compressive strength; this is due to agglomeration takes place when the resin contribution increases.

The damping ratios (ξ) were estimated using the half power band method using equation (1):

Table 1: Maximum mechanical properties of composites.

Sample code	Tensile strength (MPa)	Flexural strength (MPa)	Impact strength (J)
CP15a	372	411	27.1
CP20a	360	396	26.3
CP15b	374	420	26.4
CP20b	369	412	26.8

The variations in the damping ratio are as shown in Table 3. It reveals that the pebble 15% ratios normally produce a higher damping ratio at both set of composites. The damping ratio shows the same trend as that of com- pressive strength for all types of composites. Further increase in the filler ratio decreases the damping ratio due to lose of bonding properties of the composite. The damping values and compressive strength show that the 15% filler promotes higher bonding strength. So, the rate of transmission of cohesive force is better in the case of a 15% filler compared with that of a 20% filler.

3.3. Dynamical Mechanical Analysis. Figure 3 shows the dynamic mechanical parameters at a frequency of 1Hz. Stiffness imposed by the fillers is blamed for the increase in modulus. Fillers increase the flexibility of polymeric mate- rials while lowering their viscosity. Tg values of the epoxy composite does not show any significant variations. The restricted mobility

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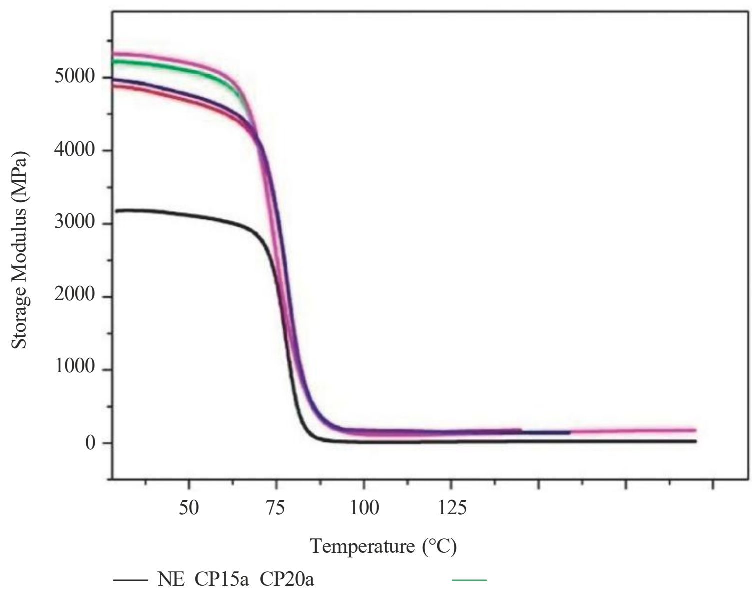
is caused by composites' crosslinked three-dimensional structures.

When compared to plain epoxy, the composites loaded with filler had a higher storage modulus in the first glassy stage. At 75 to 80 degrees Celsius, the storage modulus of clean epoxy and filler-loaded composites is nearly identical.

This is attributed to matrix softening and loss of filler-matrix adhesion, and it was a substantial contributor to the strength loss found at high temperatures. The filler enhances the Tg of the polymer matrix by improving the contact between the matrix and the filler and restricting the mobility of the molecules.

3.4. Thermal Properties. The thermogravimetric analysis was used to determine the thermal stability of the epoxy com- posites as shown in Figure 4. The thermal stability of the epoxy matrix increases dramatically with the inclusion of pebble fillers and epoxy/carbon fibre composites, according to TGA thermograms. From this, the filler-matrix degrades later than the neat resin, thermogravimetric curves for the composites are similar mass loss process starting at around 400°C, because comparing the wt. loss of the composites up to 50%, there is no considerable variation in the thermal stability between the composites. The pebble filler-reinforced composite matrices have a higher char residue when



compared to the neat epoxy. Very little variation only can see in this final char values with addition of a 15% and 20% pebble filler. However, the presence of the pebble filler in- termediary thermal stability between fillers and matrix, showing synergistic interaction.

4. Conclusions

The performance of engineering materials is evaluated based on their response to tensile, compressive, and dynamic loading under both standard and challenging operating conditions. In the present study, the incorporation of pebble fillers into carbon fibre-reinforced epoxy composites produced synergistic effects, resulting in enhanced mechanical and thermal performance. Experimental results demonstrated that the inclusion of pebble fillers and carbon fibres significantly improved the tensile, flexural, and impact strengths of the composites. Thermogravimetric analysis further revealed that the pebble-filled carbon fibre/epoxy composites exhibited greater thermal stability than the neat epoxy matrix, as indicated by an increase in char residue from 1.6% to 24.8% at 800 °C.

Data Availability

The data used to support the findings of this study are in- cluded within the article. Further data or information are available from the corresponding author upon request.

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