Mechanical Behaviour and Tensile Strength Analysis of Natural Fiber-Reinforced Epoxy Composites: A Study on SEM, Thermal and Chemical Properties

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Publication Date: 2025/11/21

Abstract: Natural fiber-reinforced epoxy composites have become a subject of significant research due to their eco-friendly nature, lightweight properties, and competitive mechanical performance compared to traditional synthetic composites. This study focuses on the mechanical behavior and tensile strength characteristics of natural fiber-reinforced epoxy composites and correlates them with microstructural, thermal, and chemical analyses. The investigation emphasizes the use of advanced techniques such as scanning electron microscopy (SEM), thermogravimetric analysis (TGA), and Fourier-transform infrared spectroscopy (FTIR) to understand the fiber–matrix interface, thermal stability, and chemical bonding mechanisms. The results show that appropriate fiber surface treatments and optimized fiber loading enhance the tensile strength and interfacial adhesion between the natural fibers and epoxy matrix. The analysis further reveals that the improved thermal resistance and chemical compatibility contribute to the composite's superior performance in engineering applications. This comprehensive characterization provides a framework for designing high-strength, sustainable composite materials for structural, automotive, and aerospace applications.

Keywords: *Natural Fibers, Epoxy Composites, Tensile Strength, Mechanical Properties, SEM, TGA, FTIR, Thermal Stability, Fiber–Matrix Adhesion, Sustainable Materials.*

How to Cite: Durai S.; Sangeeth Kumar V.; Suriya Prakash B.; Dhanish P. (2025). Mechanical Behaviour and Tensile Strength Analysis of Natural Fiber-Reinforced Epoxy Composites: A Study on SEM, Thermal and Chemical Properties. *International Journal of Innovative Science and Research Technology*, (ICMST–2025), 43-48. https://doi.org/10.38124/ijisrt/25nov752

I. INTRODUCTION

In recent years, the search for sustainable and high-performance materials has encouraged a shift from conventional synthetic fibers to natural fiber reinforcements in polymer composites. Natural fibers such as jute, hemp, flax, sisal, and coir are abundantly available, renewable, biodegradable, and low-cost. They have shown excellent potential for use in polymer matrices such as epoxy, polyester, and polypropylene, particularly in semi-structural and structural applications. Among polymer matrices, epoxy resin is one of the most widely used due to its high adhesive strength, good dimensional stability, and chemical resistance.[1-4]

However, natural fibers possess inherent variability in composition, surface morphology, and moisture absorption, which affect their compatibility with hydrophobic polymer matrices. As a result, understanding the mechanical behavior, especially tensile properties, is vital to ensure reliable performance. The fiber–matrix interface plays a crucial role in transferring load efficiently from the matrix to the reinforcement. Weak bonding leads to fiber pull-out and debonding under stress, which reduces the mechanical integrity of the composite.[5-15]

Advanced characterization techniques such as scanning electron microscopy (SEM), thermogravimetric analysis (TGA), and Fourier-transform infrared spectroscopy (FTIR) provide valuable insights into the microstructural, thermal, and chemical features of the composite system.[16]

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/25nov752

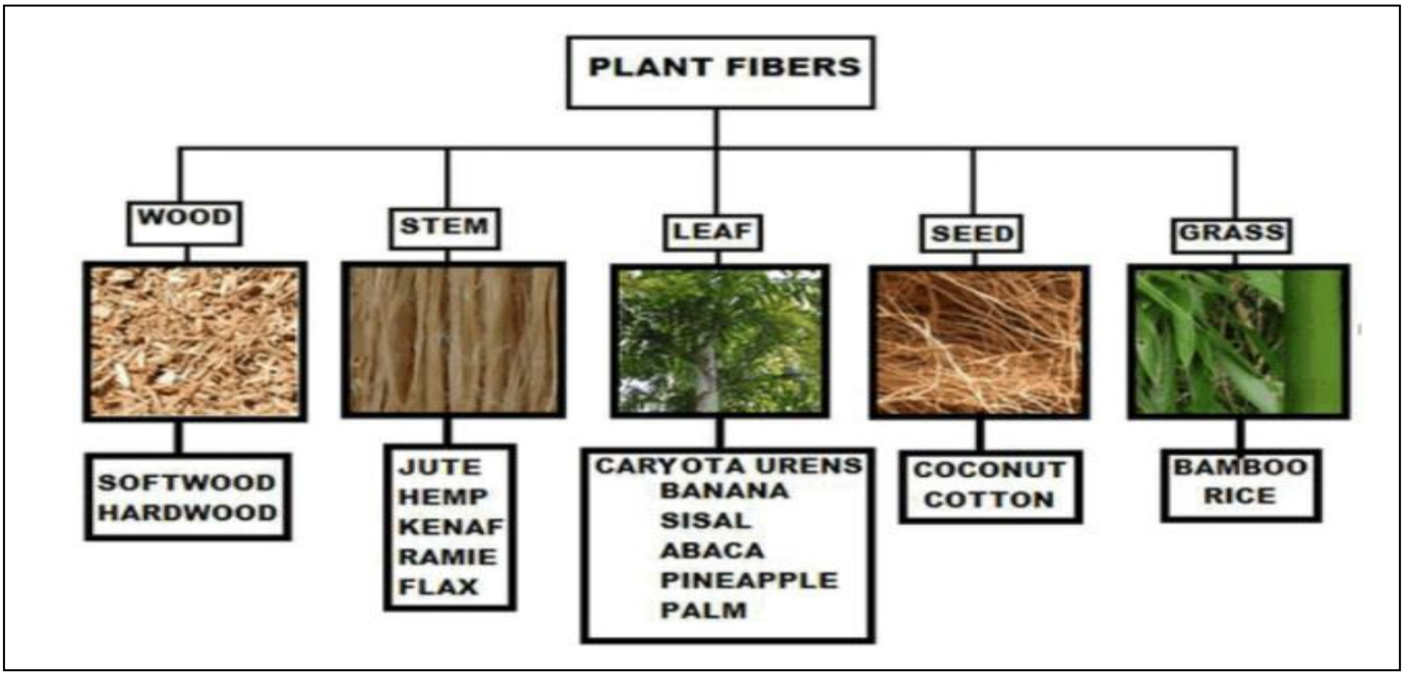

Fig 1 Classification of Plant Fibers (Image Courtesy: Researchgate.net)

These analyses reveal the quality of adhesion, the degradation behavior under heat, and the chemical functionalities that influence composite performance. The combination of these parameters governs the overall tensile strength and mechanical durability of natural fiber-reinforced epoxy composites.[17-21]

Thus, this paper aims to examine the tensile behavior of natural fiber–reinforced epoxy composites and correlate it with microstructural, thermal, and chemical characteristics. Such comprehensive understanding is essential to optimize the design and processing of natural fiber composites for engineering applications.[22-24]

II. MATERIAL PREPARATION AND EXPERIMENTAL METHODS

The preparation of natural fiber–reinforced epoxy composites involves several critical steps, including fiber extraction, surface treatment, composite fabrication, and testing. The choice of natural fiber and surface treatment significantly influences the mechanical performance of the resulting composite.[25, 26]

➢ *Fiber Preparation and Treatment*

Natural fibers are first extracted from plant sources through mechanical or retting processes, depending on the fiber type. After extraction, they are cleaned and dried to remove impurities and moisture. A chemical surface treatment, typically using an alkali solution (NaOH), is applied to enhance surface roughness and remove lignin, hemicellulose, and waxes. This treatment exposes cellulose fibrils, improving mechanical interlocking with the epoxy resin. Some studies also use silane or peroxide coupling agents to improve chemical bonding at the interface.[27-31]

➢ *Composite Fabrication*

The epoxy matrix is prepared by mixing the resin with a hardener in a specific stoichiometric ratio. The treated fibers are arranged either in unidirectional or random orientations, and the epoxy mixture is poured into a mold to form the composite laminate. The composite is cured under controlled temperature and pressure to ensure uniform cross-linking of the resin.[32-35]

➢ *Mechanical Testing*

The tensile behavior of the composites is evaluated using a universal testing machine (UTM) according to ASTM standards. Parameters such as ultimate tensile strength, Young's modulus, and elongation at break are measured. These values provide direct insights into the load-bearing capacity and stiffness of the composite material.

By optimizing fiber volume fraction and treatment conditions, the mechanical performance of the composites can be tailored for specific applications such as lightweight panels, casings, and automotive interiors.[36-42]

III. MECHANICAL AND TENSILE BEHAVIOR

The mechanical behavior of natural fiber-reinforced epoxy composites depends on various factors, including fiber type, fiber–matrix adhesion, fiber orientation, and loading conditions. Among the mechanical properties, tensile strength is one of the most important indicators of performance. It represents the ability of the material to resist deformation or failure under axial loading.[43, 44]

➢ *Tensile Strength and Modulus*

The tensile strength of untreated natural fiber–epoxy composites is often lower due to poor interfacial adhesion caused by surface impurities and hydrophilic nature of fibers. However, after alkali or silane treatment, significant

ISSN No: -2456-2165 https://doi.org/10.38124/ijisrt/25nov752

improvement in tensile strength is observed. The enhanced interfacial bonding allows more efficient stress transfer from the matrix to the fibers, reducing the risk of fiber pull-out and interfacial debonding. In many cases, a moderate fiber loading (around 20–30 wt%) provides the best balance between strength and toughness, as excessive fiber content can lead to void formation or agglomeration, weakening the composite.[45-48]

- *Failure Mechanism*

SEM analysis of fractured surfaces provides visual evidence of the failure mechanisms involved. In well-bonded composites, fiber breakage dominates, indicating effective stress transfer. In poorly bonded composites, fiber pull-out and matrix cracking are observed, demonstrating interfacial failure. This distinction is critical because the interface quality directly controls mechanical durability under cyclic or impact loading.[49-51]

- *Influence of Fiber Orientation*

The orientation of fibers also plays a vital role in tensile behavior. Unidirectional composites exhibit high tensile strength along the fiber direction but weak transverse strength. Randomly oriented composites, on the other hand, provide isotropic mechanical response but lower overall stiffness. By aligning fibers strategically or using woven mats, the mechanical performance can be optimized for specific load-bearing requirements.[52]

Overall, natural fiber–reinforced epoxy composites exhibit an excellent combination of strength, stiffness, and ductility, making them ideal for medium-load applications where sustainability and weight reduction are priorities.

IV. SEM, THERMAL, AND CHEMICAL CHARACTERIZATION

- *Scanning Electron Microscopy (SEM)*

SEM provides crucial information about the microstructure and fracture morphology of the composite. The images reveal how effectively the fibers are bonded to the epoxy matrix. After chemical treatment, the fiber surfaces appear rougher, with visible fibrillation that promotes mechanical interlocking. SEM micrographs of fractured specimens often show fewer voids and better adhesion for treated fibers compared to untreated ones. The quality of interfacial bonding observed under SEM correlates directly with the tensile strength values obtained from mechanical tests.[53, 54]

- *Thermal Analysis (TGA and DSC)*

Thermal analysis helps to assess the stability of the composite under heat. Thermogravimetric analysis (TGA) shows three major stages of decomposition: moisture loss below 120°C, hemicellulose degradation between 200°C and 300°C, and cellulose decomposition between 300°C and 400°C. The residual char content at 600°C provides information about thermal resistance. Treated fibers exhibit higher degradation onset temperatures, indicating improved thermal stability due to the removal of thermally unstable components.

Differential scanning calorimetry (DSC) measures thermal transitions such as glass transition (Tg) and melting behavior. The Tg of the composite typically increases after surface treatment, suggesting stronger fiber–matrix interaction and restricted molecular mobility within the epoxy network.

- *Chemical Characterization (FTIR)*

Fourier-transform infrared spectroscopy (FTIR) reveals the functional groups and chemical bonding mechanisms within the composite. Characteristic peaks around 3400 cm^{-1} correspond to –OH stretching of cellulose, while peaks at 1730 cm^{-1} indicate carbonyl groups in hemicellulose. After treatment, reduced intensity in hemicellulose and lignin peaks confirms their removal, leading to enhanced compatibility with the hydrophobic epoxy resin. Additionally, the emergence of Si–O–Si and Si–O–C bonds in silane-treated fibers indicates improved chemical bonding between fiber and matrix.

V. DISCUSSION AND CONCLUSION

The combination of mechanical, microstructural, thermal, and chemical analyses provides a comprehensive understanding of the performance of natural fiber–reinforced epoxy composites. The findings demonstrate that surface-treated fibers significantly improve tensile strength and stiffness due to enhanced fiber–matrix adhesion. SEM analysis confirms that treated fibers exhibit better interfacial bonding and fewer voids, leading to improved load transfer and reduced failure initiation sites.

Thermal analysis indicates that treated composites can withstand higher processing and operating temperatures, while FTIR studies validate the formation of stronger chemical bonds between fiber and epoxy. These improvements collectively make natural fiber–reinforced epoxy composites highly suitable for automotive panels, interior components, sporting goods, and lightweight structural parts.

The study concludes that the mechanical behavior and tensile strength of natural fiber–epoxy composites are highly dependent on the synergy between chemical treatment, interfacial morphology, and thermal stability. With continued optimization and hybridization techniques, natural fibers can effectively replace synthetic reinforcements in numerous engineering applications, offering a pathway toward sustainable, high-performance composite materials.

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