SSRG International Journal of Mechanical Engineering
ISSN: 2348-8360/ https://doi.org/10.14445/23488360/IJME-V11I2P102

Volume 11 Issue 2, 16-23, February 2024

Original Article

Impact of Bran Filler Amount on Flax Fiber Reinforced Epoxy Composite - Mechanical and Thermal Properties for Secondary Structural Applications

T. Raja[1], D. Yuvarajan[2], V. Sundaram[2*], S. Vidhya Lakshmi[2], V.P. Veeraragavan[3]

[1]Material Science Lab, Department of Prosthodontics, Saveetha Dental College and Hospitals, SIMATS, Tamilnadu, India.
[2]Saveetha School of Engineering, Saveetha Institute of Medical and Technical Sciences (SIMATS), Tamilnadu, India.
[3]Centre of Molecular Medicine and Diagnostics, Saveetha Dental College and Hospitals,
Saveetha Institute of Medical and Technical Sciences, Saveetha University, Tamilnadu, India.

**Corresponding Author : hodbiotech.sse@saveetha.com*

Received: 07 December 2023 Revised: 11 January 2024 Accepted: 12 February 2024 Published: 29 February 2024

Abstract *- This study examines the mechanical and thermal properties of flax fibre-reinforced epoxy composites with three different concentrations of bran filler to assess their potential for secondary structural applications. The mechanical parameters, such as tensile strength, flexural modulus, and Izod impact resistance, were investigated systematically, in addition to thermal properties, including thermal conductivity, coefficient of linear thermal expansion, and heat deflection temperature. SEM was used to analyse the fracture surfaces after tensile failure to understand the material's failure mechanisms. Adding bran filler to flax fiber reinforced epoxy composites had a notable impact on mechanical and thermal properties. Testing showed that the ideal bran filler improved tensile strength and flexural modulus without compromising impact resistance, indicating a synergistic reinforcement effect. Thermal investigation revealed that using bran filler enhanced thermal stability by raising heat deflection temperatures and regulating thermal conductivity and expansion coefficients to meet the demands for thermal resilience in secondary structural applications. Scanning Electron Microscopy (SEM) research revealed how the bran filler altered the fracture behaviour of the composite by enhancing the adhesion between fibres and matrix and improving energy dissipation processes. The results indicate that flax fibre-reinforced epoxy composites, enhanced with bran filler, offer a promising, eco-friendly option for secondary structural uses requiring mechanical strength and heat resistance.*

Keywords *- Flax fibre, Bran filler, Mechanical properties, Thermal analysis, Surface analysis.*

1. Introduction

Natural fibres have garnered significant attention for their role in composite material fabrication, primarily due to their eco-friendly nature, cost-effectiveness, and renewable properties [1]. These fibres, derived from plants, animals, or minerals, provide a sustainable option compared to synthetic fibres, helping to lessen the environmental footprint. They improve the mechanical properties, rigidity, and longevity of composites while also promoting biodegradability and reducing carbon footprints. Incorporating natural fibres into polymers or resins creates lighter composites with enhanced thermal and acoustic insulation qualities compared to synthetic materials [2].

This characteristic is particularly advantageous in industries such as automotive and aerospace, where weight reduction is crucial for fuel efficiency. Natural fibres such as hemp and flax have tensile strengths ranging from 55-90 MPa to 34-103 MPa, providing significant reinforcement to composite structures. Their thermal conductivity ranges from 0.04 to 0.06 W/mK, enhancing the composites' thermal insulation qualities.

Moreover, the elongation at break for these fibres is about 1.2 to 3.2%, indicating their flexibility and resilience [3]. The moisture absorption rate varies significantly among different types of natural fibres, often seen as a drawback; however, it can be managed through appropriate treatments. Manufacturers can balance strength, weight, and environmental sustainability by incorporating these fibres into composites, making natural fibre-reinforced composites a compelling choice for eco-friendly material solutions.

Kenaf fibres, derived from the kenaf plant, are increasingly recognized for their remarkable properties when integrated into composite materials [4]. These fibres exhibit a density of approximately 1.4 g/cm³, positioning them as a lightweight alternative suitable for various applications, particularly in the automotive and construction sectors, indicating their stiffness and ability to resist deformation under load. Kenaf fibres also have a thermal conductivity value that falls roughly between 0.033 and 0.04 W/mK, enhancing the thermal insulation capability of the composites in which they are used [5].

The moisture absorption rate is another critical aspect, with kenaf fibres showing a tendency to absorb moisture, which can be mitigated through appropriate treatment processes to maintain the material’s integrity in humid environments. Overall, kenaf fibre composites offer a sustainable, high-performance material choice that aligns with the increasing demand for environmentally friendly and renewable resources in the manufacturing sector [6].

Natural fibre composite materials exhibit distinctive thermal properties that significantly contribute to their applicability across various sectors. The thermal conductivity of these composites is relatively low, typically ranging from 0.03 to 0.5 W/mK, which underscores their effectiveness as insulating materials. This characteristic is precious in the construction and automotive industries, where thermal efficiency can lead to energy savings and enhanced comfort [7].

Natural fibre composites have a specific heat capacity ranging from 1.3 to 1.6 J/gK, allowing them to absorb and store heat efficiently. The thermal breakdown of natural fibres begins from 220°C to 380°C, demonstrating their thermal resilience at moderate temperatures. This factor is essential for applications subject to fluctuating temperatures, guaranteeing the durability of the composite material in the long run [8].

Natural fibre composites have a low thermal expansion coefficient ranging from 5 to 30 µm/mK, which helps to reduce dimensional variations caused by temperature changes, thereby preserving the structural integrity of the composite [9]. These thermal properties, combined with their environmental benefits, position natural fibre composites as a compelling choice for industries aiming to leverage sustainable materials without compromising performance. These fibres exhibit a heterogeneous and complex structure characterized by a cellular arrangement with a hollow lumen and a high aspect ratio, contributing to their lightweight nature. The surface morphology of natural fibres is typically rough and uneven, providing excellent mechanical interlocking when combined with matrix materials, enhancing the bond strength in composites [10].

This roughness is pivotal for adhesion in composite fabrication, influencing both mechanical properties and durability. Microscopically, natural fibres are composed of cellulose, hemicellulose, and lignin, with the cellulose microfibrils arranged in a spiral pattern around the lumen, contributing to the fibre’s strength and stiffness.

Natural waxes and oils on the fibre surface can affect matrix adhesion, necessitating surface treatments to improve compatibility. Natural fibres have a diameter range of 10 to 50 micrometres, which impacts their flexibility and tensile strength. Flax-based natural fibre composites garner more interest in industrial applications because of their outstanding characteristics and sustainability benefits. Flax composites are utilized in the automotive industry for interior components and body panels to reduce vehicle weight and enhance fuel efficiency [11].

Similarly, in the construction industry, flax fibres are incorporated into panels and insulation materials for their thermal properties and sustainability credentials. Additionally, their natural vibration-damping qualities are leveraged to enhance performance in manufacturing sporting goods, such as tennis rackets and bicycles. Adopting flax natural fibre composites supports the transition towards greener manufacturing practices and opens new avenues for product innovation in various industries [12].

The above literature was used to identify the research gap for this research; in this work, the fabrication of novel composite material was done using flax fibre, bran filler, and epoxy matrix under the hand layup technique. Further, the material stability was analyzed by conducting mechanical and thermal tests and examining the failure of this composite material using SEM analysis.

2. Materials and Experimental Methods

This research uses flax stem fibre collected as bidirectional woven fabric, bran particles, and epoxy resin with LY 556 araldite hardener with a 10:1 ratio from SM composite, Chennai, India.

2.1. Fabrication Process of FF Composite

The hand layup process for fabricating flax fibre-reinforced bran filler blended epoxy matrix composites involves a meticulous, step-by-step methodology that ensures the integration of natural fibres and fillers into a cohesive composite material. Initially, the process begins with preparing the mould, which is carefully cleaned and treated with a release agent to ensure easy composite removal after curing.

The epoxy resin is then mixed with a hardener at a precise ratio, to which bran filler is added and thoroughly blended to achieve a uniform dispersion. This mixture enhances the matrix’s mechanical properties and sustainability aspect. Subsequently, flax fibres, selected for their high strength and environmental benefits, are cut to the desired size and laid onto the mould [13].

The resin-bran filler mixture is applied over the flax fibres using a brush or roller, ensuring complete saturation and avoiding air entrapment. Layers of flax fibres are placed one after the other, with each layer being thoroughly wetted out with the resin-filler mixture. This layering process is critical for achieving the composite's desired thickness and mechanical properties.

Once the layup is complete, the composite can cure under ambient conditions under uniform pressure and remove any excess resin and air bubbles for up to 24 hours. After curing, the composite is moulded, revealing a lightweight, strong, and sustainable material that leverages the unique properties of flax fibres and bran filler within an epoxy matrix. This hand layup process is favoured for its simplicity, cost-effectiveness, and adaptability in producing composites with complex shapes and tailored properties [14]. Figure 1 shows the fabrication of a flax fibre composite. The weight ratio of the flax/bran/epoxy composite is given in Table 1.

Table 1. Weight ratio of flax/bran/epoxy composite

Sample	Weight of Flax Fibre (FF) in g	Weight of Bran Filler in g	Weight of Epoxy Matrix in g
X	120	5	115
Y	120	10	110
Z	120	15	105

Fig. 1 Fabrication process of flax fiber composite

2.2. Experimental Testing of FF Composite

Experimental testing of flax fibre-reinforced bran filler-loaded epoxy composites encompasses a comprehensive suite of tests to evaluate mechanical, thermal, and structural properties, adhering to ASTM standards. Tensile properties are determined using ASTM D638, where specimens are subjected to uniaxial tension until failure, providing insights into the composite's strength and elongation capabilities.

Flexural properties are assessed under a three-point bending test as per ASTM D790, which measures the material's ability to resist deformation under load, indicative of its stiffness and bending strength. The Izod impact test, following ASTM D256, evaluates the composite's toughness by measuring the energy absorbed upon impact, offering a gauge of its resistance to sudden forces [15].

Thermal properties are examined through several tests: Thermal conductivity is assessed using ASTM E1952, which determines the material's ability to conduct heat, which is critical for applications requiring thermal management. The Coefficient of Linear Thermal Expansion (CLTE) is measured under ASTM E831, providing essential data on how the composite's dimensions change with temperature variations.

Heat Deflection Temperature (HDT) is determined according to ASTM D648, indicating the temperature at which the composite deforms under a specified load, essential for understanding its performance in high-heat applications, ASTM E1131-10 standard was used to conduct the thermogravimetric analysis, which is used to analyze the thermal degradation temperature of FF composite [16].

Furthermore, the composite's microstructure and fibre-matrix interface are scrutinized using Scanning Electron Microscopy (SEM) analysis; However, no specific ASTM standard is dedicated to SEM analysis for this material class; it is commonly performed to understand the morphology and potential failure mechanisms at the microscopic level. This analysis provides invaluable insights into the composite's internal structure, highlighting the distribution of fibres and fillers and the quality of the fibre-matrix adhesion, which are pivotal in tailoring the composite's properties for specific applications [17].

These experimental tests, grounded in ASTM standards, offer a robust framework for characterizing and optimizing the performance of flax fiber reinforced bran filler-loaded epoxy composites.

3. Results and Discussion

3.1. Mechanical Properties of FF Composite

Figure 2 shows the mechanical properties of flax fibre composite. The tensile strength of flax fibre-reinforced bran filler-loaded epoxy composites has been the subject of considerable research due to its importance in determining the composite's suitability for structural applications [18]. Research indicates that incorporating flax fibres significantly improves the tensile strength of the composite material. Sample Z exhibited the highest tensile strength at 29.19 MPa, whereas sample X had the lowest at 21.43 MPa, 27.5% lower than sample Z due to bran filler. Factors like the fiber volume percentage, fiber orientation, and the quality of the fibre-matrix interface cause this fluctuation. Specifically, composites with a higher volume fraction of flax fibres tend to exhibit higher tensile strength due to the efficient load transfer between the matrix and the fibres.

Moreover, adding bran filler to the epoxy matrix can further influence the tensile strength. While the filler can improve the stiffness and impact resistance of the composite, excessive amounts may lead to a reduction in tensile strength due to possible accumulation and weak interfaces within the matrix. Optimizing the flax fibres to bran filler ratio is crucial to balancing strength with other desired properties, such as flexibility and impact resistance.

Overall, the tensile strength of these composites highlights their potential as a sustainable alternative to traditional materials in various engineering applications, provided that the composite formulation is carefully tailored to meet specific performance criteria. Figure 3 shows the Stress vs Strain curve during the composite tensile test.

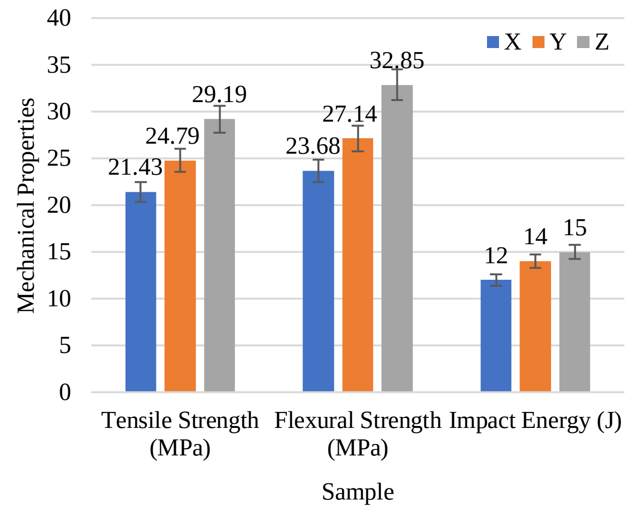

Fig. 2 Mechanical properties of flax fibre composite

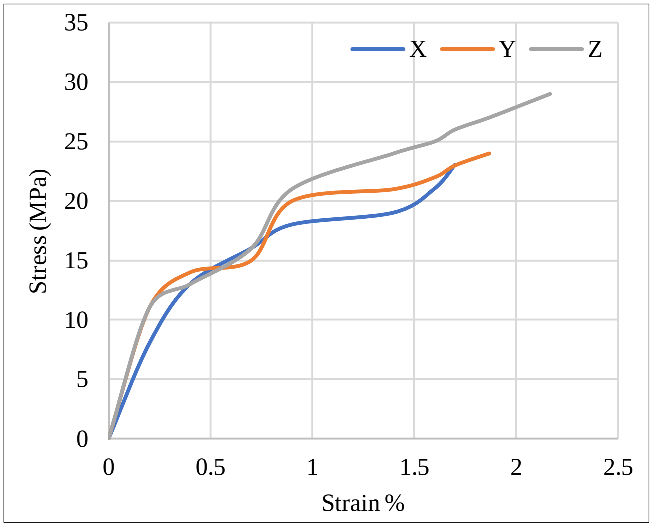

Fig. 3 Stress Vs. Strain curve during the tensile test of composite

The flexural strength of flax fibre-reinforced bran filler-loaded epoxy composites is a critical parameter that reflects the material's ability to resist deformation under bending loads. Research indicates that these composites can exhibit flexural strength values in sample Z at 32.85 MPa and in samples X Y at 23.68 and 27.14 MPa, respectively. Several factors influence this comprehensive range, including the orientation and content of flax fibers, the proportion of bran filler, and the overall quality of the epoxy matrix.

Specifically, the alignment of flax fibres along the direction of applied stress significantly enhances flexural performance due to the effective load transfer mechanisms between the fibres and the matrix [8]. Bran filler can modify the matrix properties, affecting the composite's rigidity and flexural strength. An optimal filler content can lead to an improved stress distribution and increased resistance to bending, whereas excessive filler may result in stress concentrations and reduced flexural strength.

Achieving a balanced composite formulation is essential for maximizing flexural strength, making these materials suitable for applications where resistance to bending and structural integrity are paramount. By employing precise material design and processing methods, it is possible to create flax fibre-reinforced bran filler-loaded epoxy composites that can be tailored to meet specific flexural strength needs. This provides a sustainable and performance-driven choice for a variety of sectors.

The Izod impact energy absorption of epoxy composites reinforced with flax fibre and bran filler indicates the material's toughness and resistance to sudden impacts. Experimental findings suggest these composites can absorb impact energy ranging from 12 to 15 J. The variation is mainly caused by the composite's internal structure, which involves the distribution and alignment of flax fibres, the quantity of bran filler, and the interaction between the fibres and the epoxy matrix. The alignment of flax fibres perpendicular to the impact direction enhances impact resistance by improving energy dissipation mechanisms. Option available for diverse sectors.

Additionally, incorporating bran filler can affect the composite's impact properties; a moderate filler can improve toughness by promoting energy absorption within the matrix [2]. However, excessive filler may decrease impact energy absorption due to potential agglomerations and weak spots that can initiate crack propagation upon impact. Optimizing the composite formulation by carefully balancing the fibre orientation, filler content, and matrix properties is critical to maximizing impact energy absorption. This optimization allows for developing flax fiber reinforced bran filler loaded epoxy composites with enhanced durability and resilience, making them suitable for applications requiring materials that can endure dynamic and impact loads.

3.2. Thermal Properties of FF Composite

Figure 4 shows the thermal properties of flax fibre composite. Flax fibre-reinforced bran filler-loaded epoxy matrix composites represent a potential area of research in developing sustainable and efficient thermal insulation materials.

These composites are characterized by their unique thermal conductivity properties, which are influenced by the composition and structure of the materials used. Specifically, flax fibres are known for their excellent insulation capabilities, with the thermal conductivity of this FF composite ranging from 1.15 to 2.18 W/mK, which contributes to the overall thermal performance of the composite [11].

When combined with bran fillers, these natural fibres are dispersed within an epoxy matrix, leading to a composite material that exhibits a balanced combination of mechanical strength and thermal insulation. The epoxy matrix, with a thermal conductivity of 0.35 to 0.40 W/(mK), is a binder that integrates the flax fibres and bran fillers, enhancing the composite's structural integrity while maintaining a low thermal conductivity [12].

The resulting flax fibre-reinforced bran filler-loaded epoxy matrix composites typically exhibit thermal conductivity values that are significantly lower than traditional composites, often found to be in the range of 2.74 to 3.19 W/(mK), due to the bran filler content and fibre orientation.

This low thermal conductivity is advantageous for applications requiring efficient thermal insulation, such as building materials and automotive components, where energy efficiency and sustainability are key considerations. The synergistic effect of the flax fibres and bran fillers within the epoxy matrix not only improves the composite's environmental footprint but also offers a viable pathway to enhance the thermal insulation properties of composite materials.

The Coefficient of Linear Thermal Expansion (CLTE) is a critical property for materials used in various applications, especially in environments subject to temperature variations. The property of these composites is greatly affected by the distinct combination of components utilized in flax fibre-reinforced bran filler-loaded epoxy matrix composites.

Flax fibres, recognized for their lightweight and robust properties, improve the thermal stability of the composite when mixed with bran filler. The epoxy resin acts as the matrix, binding the reinforcements together and influencing the composite's thermal properties.

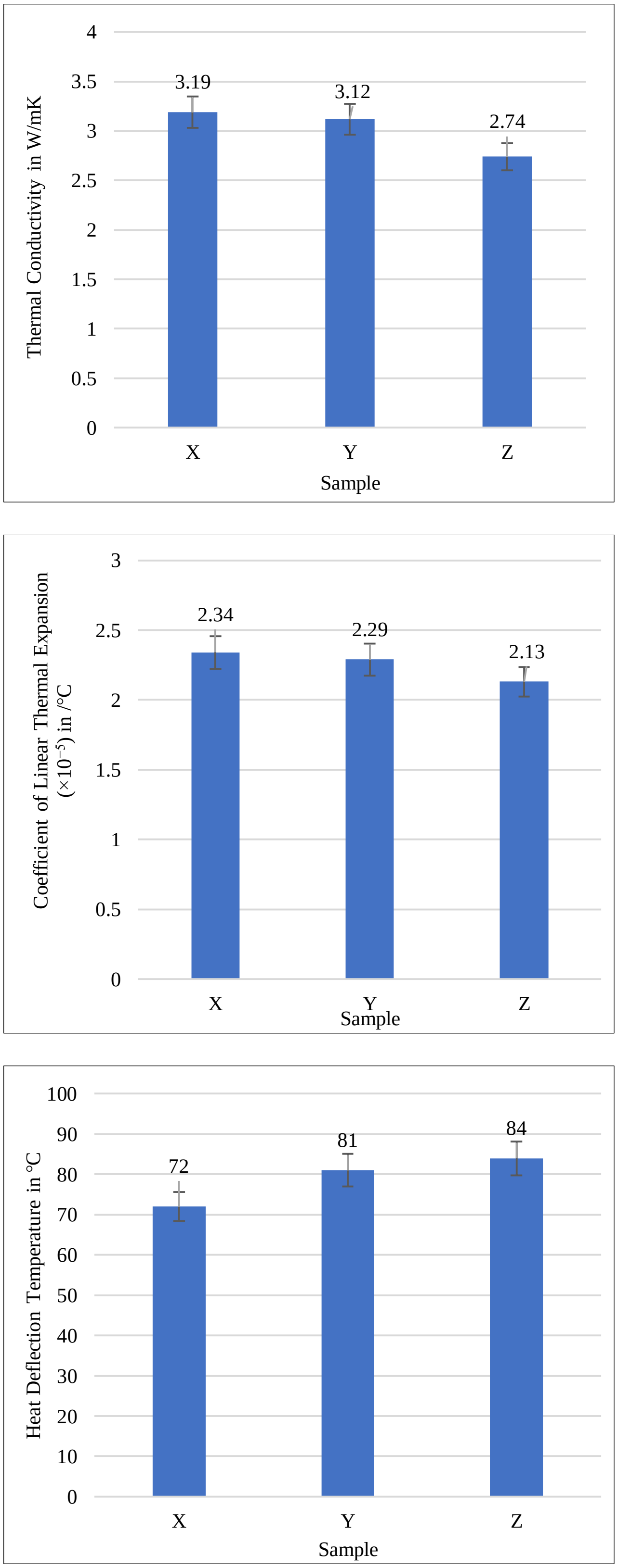

Fig. 4 Thermal properties of flax fibre composite

Research indicates that such FF composites exhibit a CLTE in the range observed for samples X, Y, and Z, which is 2.13 to 2.34 x 10^{-5}/°C. This range indicates the composite's ability to withstand thermal stress without significant dimensional changes, making it suitable for applications where thermal resistance and dimensional stability are paramount.

The specific CLTE value within this range can vary based on flax fibre, bran filler, and epoxy matrix proportions and the processing conditions under which the composite is fabricated. Such tailored thermal expansion characteristics are crucial for designing environmentally friendly and functionally versatile materials, catering to the needs of industries seeking sustainable alternatives to conventional materials.

The Heat Deflection Temperature (HDT) of flax fibre-reinforced bran filler-loaded epoxy matrix composites demonstrates remarkable thermal stability, pivotal for applications requiring dimensional stability under thermal stress. Through experimental evaluations, it has been observed that incorporating flax fibres and bran fillers into the epoxy matrix notably enhances the composite's thermal resistance.

Specifically, these composites exhibit a heat deflection temperature range for samples X to Z of 72 to 84°C. This enhancement is attributed to the synergistic effect of the flax fibres and bran fillers, which provide an effective thermal barrier, thereby reducing the thermal deformation under applied stress [14].

The resultant composite material maintains its structural integrity at elevated temperatures and offers an eco-friendly alternative to traditional petroleum-based composites, aligning with sustainable materials development initiatives.

3.3. Thermogravimetric Analysis of FF Composite

Figure 5 shows the thermal stability of the FF composite. Thermo-Gravimetric Analysis (TGA) offers essential information on the heat stability and breakdown properties of composites made of flax fibre reinforced with bran filler-filled epoxy matrix.

The investigation shows that the first weight loss, primarily due to moisture evaporation from the composite, happens at around 100°C. Between 150°C and 250°C, a notable decrease in weight occurs due to the breakdown of the organic elements in the flax fibres and bran filler. This phase is marked by a 30% reduction in weight, showing the decomposition of cellulose and hemicellulose components in the composite [16].

Weight loss slows as the temperature rises above 350°C, and this trend persists until reaching 400°C. This phase is linked to the deterioration of the epoxy matrix and the remaining elements of the filler and fibre. At 400°C, the residual weight, which includes the inorganic component and charred residue, accounts for almost 25% of the original composite weight. The TGA analysis highlights the composite's thermal durability and probable degradation routes at high temperatures, offering crucial insights for its use in situations requiring thermal solid resistance.

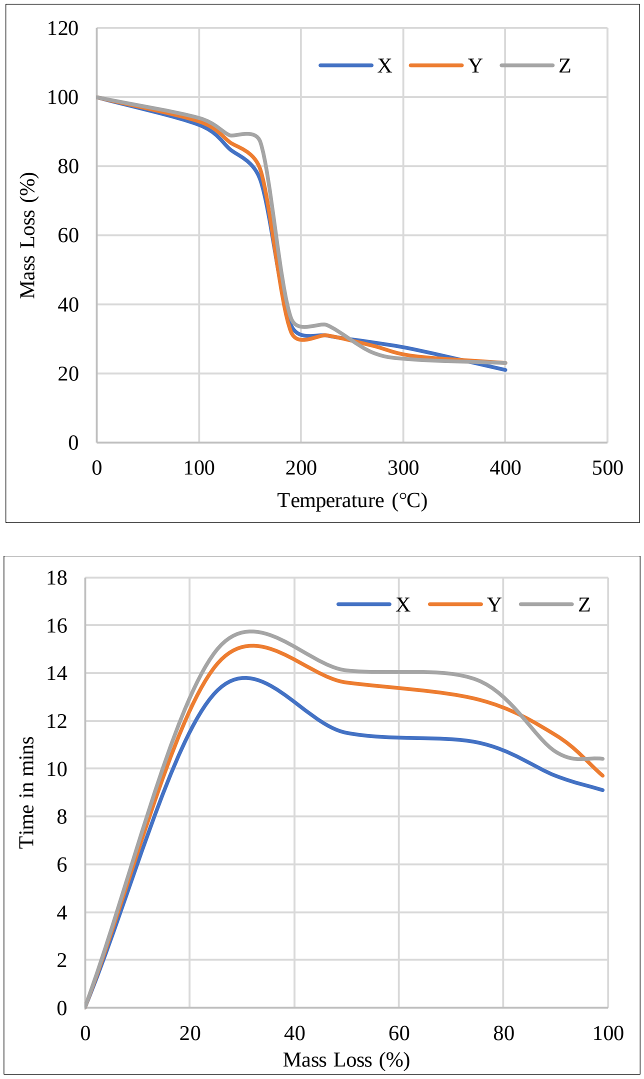

Fig. 5 Thermal stability of FF composite

3.4. SEM Morphology of FF Composite

During tensile failure, the SEM surface morphological analysis on flax fiber reinforced bran filler loaded epoxy matrix composites reveals intricate details about the material's fracture mechanisms. Scanning Electron Microscope images after tensile testing show a varied fracture surface with fibre pull-out, matrix cracking, and void formation [3].

This observation indicates a sophisticated bonding at the interface between the flax fibres, bran filler, and the epoxy matrix. Flax fibres deeply entrenched in the matrix and properly soaked in epoxy show less fibre pull-out, suggesting a better bond between the fibre and the matrix. Conversely, regions showing significant fibre pull-out and voids point to weaker interfacial bonds. The presence of bran filler particles can be seen to affect the fracture path, often diverting cracks and contributing to energy dissipation during failure [17].

These morphological features underscore the impact of fibre and filler incorporation on the composite's mechanical performance, highlighting the crucial role of interfacial adhesion in determining the material's toughness and failure resistance [18]. Figure 6 shows the SEM image of the flax fibre composite.

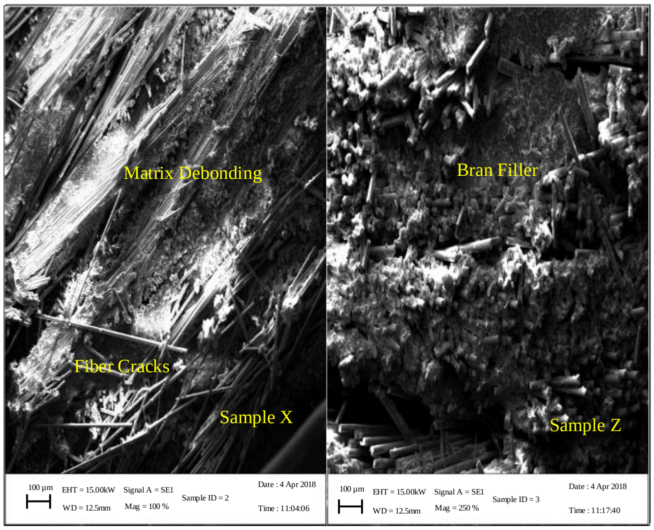

Fig. 6 SEM image of flax fibre composite

4. Conclusion

The research on the effect of bran filler loading on flax fibre-reinforced epoxy composites has provided significant insights into these materials' mechanical and thermal performance, underscoring their potential for secondary structural applications.

The study found that adding bran filler to the composite matrix improves mechanical parameters like tensile strength, flexural modulus, and impact resistance. This improvement is attributed to the effective stress transfer facilitated by the bran filler, which also contributes to the toughness and durability of the composite. Thermally, adding bran filler was found to augment the composite's thermal stability, as evidenced by increased heat deflection temperatures. This indicates a better resistance to deformation under thermal stress, making these composites suitable for applications where temperature variations are a concern.

Furthermore, the optimized thermal conductivity and expansion coefficients suggest that these materials can efficiently manage thermal stresses, further enhancing their applicability in structural contexts. Scanning Electron Microscope investigations supported these results by demonstrating the beneficial effect of bran filler on the bonding between the flax fibres and the epoxy matrix.

This improved adhesion is crucial for the composite's mechanical integrity and thermal stability, facilitating its performance under load and during thermal cycling. Ultimately, the research shows that flax fibre-reinforced epoxy composites, with carefully adjusted bran filler content, have improved mechanical characteristics and thermal stability.

These characteristics make them viable, sustainable alternatives for secondary structural applications, offering an eco-friendly option without compromising performance. The research suggests a future investigation into utilizing flax fibre composites in advanced engineering applications to enhance sustainability in material design.

References

[1] Devyani Thapliyal et al., "Natural Fibers Composites: Origin, Importance, Consumption Pattern, and Challenges," *Journal of Composites Science*, vol. 7, no. 12, pp. 1-44, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[2] S.M. Kalbin Salim Turjo et al., "Mechanical Characterization and Corrosive Impacts of Natural Fiber Reinforced Composites: An Experimental and Numerical Approach," *Polymer Testing*, vol. 125, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[3] Barshan Dev et al., "Mapping the Progress in Natural Fiber Reinforced Composites: Preparation, Mechanical Properties, and Applications," *Polymer Composites*, vol. 44, no. 7, pp. 3748-3788, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[4] Vikas Mittal, *Spherical and Fibrous Filler Composites*, Wiley-CH Verlag GmbH & Co. KGaA, 2016. [Google Scholar]

[5] R. Vijay et al., "Characterization of Raw and Alkali Treated New Natural Cellulosic Fibers from Tridax Procumbens," *International Journal of Biological Macromolecules*, vol. 125, pp. 99-108, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[6] Maria-Beatrice Coltelli et al., "Chain Extension of Poly (Lactic Acid) (PLA)-Based Blends and Composites Containing Bran with Biobased Compounds for Controlling their Processability and Recyclability," *Polymers*, vol. 13, no. 18, pp. 1-26, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[7] C. Tezara et al., "Factors that Affect the Mechanical Properties of Kenaf Fiber Reinforced Polymer: A Review," *Journal of Mechanical Engineering and Sciences*, vol. 10, no. 2, pp. 2159-2175, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[8] N. Saba, M.T. Paridah, and M. Jawaid, "Mechanical Properties of Kenaf Fibre Reinforced Polymer Composite: A Review," *Construction and Building Materials*, vol. 76, pp. 87-96, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[9] S. Dinesh et al., “Influence of Wood Dust Fillers on the Mechanical, Thermal, Water Absorption and Biodegradation Characteristics of Jute Fiber Epoxy Composites,” *Journal of Polymer Research*, vol. 27, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[10] Abdul Moudood et al., “Flax Fiber and Its Composites: An Overview of Water and Moisture Absorption Impact on their Performance,” *Journal of Reinforced Plastics and Composites*, vol. 38, no. 7, pp. 323-339, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[11] Aarti P. More, “Flax Fiber-Based Polymer Composites: A Review,” *Advanced Composites and Hybrid Materials*, vol. 5, pp. 1-20, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[12] V. Mohanavel et al., “Influence of Stacking Sequence and Fiber Content on the Mechanical Properties of Natural and Synthetic Fibers Reinforced Penta-Layered Hybrid Composites,” *Journal of Natural Fibers*, vol. 19, no. 13, pp. 5258-5270, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[13] S. Jothibasu et al., “Investigation on the Mechanical Behavior of Areca Sheath Fibers/Jute Fibers/Glass Fabrics Reinforced Hybrid Composite for Light Weight Applications,” *Journal of Industrial Textiles*, vol. 49, no. 8, pp. 1036-1060, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[14] J. Andersons, E. Sparnins, and R. Joffe, “Stiffness and Strength of Flax Fiber/Polymer Matrix Composites,” *Polymer Composites*, vol. 27, no. 2, pp. 221-229, 2006. [CrossRef] [Google Scholar] [Publisher Link]

[15] L. Natrayan et al., “Influence the Graphene Filler Addition on the Tensile Behavior of Natural Kenaf Fiber-Based Hybrid Nanocomposites,” *Journal of Nanomaterials*, vol. 2022, pp. 1-8, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[16] Hongbin Li et al., “Recent Progress in Flax Fiber-Based Functional Composites,” *Advanced Fiber Materials*, vol. 4, pp. 171-184, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[17] L. Natrayan et al., “Effect of Mechanical Properties on Fibre Addition of Flax and Graphene-Based Bionanocomposites,” *International Journal of Chemical Engineering*, vol. 2022, pp. 1-8, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[18] Mohammad Asim et al., “Thermal Stability of Natural Fibers and their Polymer Composites,” *Iranian Polymer Journal*, vol. 29, pp. 625-648, 2020. [CrossRef] [Google Scholar] [Publisher Link]