EXPERIMENTAL EVALUATION OF THERMO-MECHANICAL PROPERTIES FOR BIODEGRADABLE SISAL FIBER/CORNFLOUR MATRIX COMPOSITES

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Abstract: *In the pursuit of sustainable alternatives to synthetic polymers, this study investigates the thermo-mechanical performance of biodegradable composites reinforced with sisal fiber and a cornflour-based matrix. The composite specimens were fabricated using varying weight fractions of sisal fiber through curing in the moulds prepared through 3D printing, followed by air drying. The mechanical behaviour was assessed through tensile, flexural, and impact tests in accordance with ASTM standards, revealing a significant enhancement in strength and stiffness with optimized fiber content. Thermal stability was evaluated using Thermogravimetric Analysis (TGA), which demonstrated improved thermal resistance of the fiber-reinforced matrix compared to the neat cornflour matrix. The results confirm that the incorporation of sisal fibers not only reinforces the mechanical integrity of the composite but also delays thermal degradation, making it a promising candidate for low-cost, biodegradable applications in packaging and light-load structural components. The study contributes valuable insights into the development of eco-friendly, fiber-reinforced biopolymers with balanced mechanical and thermal performance.*

1. INTRODUCTION

The growing environmental concerns associated with synthetic polymers have catalysed extensive research in the development of sustainable and biodegradable composite materials. Natural fiber-reinforced composites offer a viable alternative due to their renewability, low cost, low density, biodegradability, and relatively good mechanical properties. Among the various natural fibers available, sisal fiber (Agave sisalana) has attracted significant attention due to its high tensile strength, stiffness, availability, and compatibility with bio-based matrices. Simultaneously, cornflour (corn starch), a biodegradable polysaccharide, has emerged as an effective natural matrix material. Cornflour-based matrices exhibit good film-forming ability and are widely used in biodegradable packaging materials. However, their inherent brittleness and limited mechanical performance restrict their standalone application in structural components. Reinforcement with natural fibers such as sisal can significantly enhance their mechanical and thermal characteristics, making them suitable for broader applications. The development of sisal fiber-reinforced cornflour composites provides a sustainable route to replacing synthetic composites in lightweight, low-load applications. However, the interfacial adhesion between the hydrophilic cornflour matrix and the lignocellulosic fiber must be optimized to achieve desired performance. Moreover, the evaluation of both mechanical and thermal properties is essential to determine the practical applicability of such composites in real-world conditions. This study presents an experimental investigation into the thermo-mechanical properties of biodegradable composites fabricated using sisal fiber and cornflour matrix. Composites were prepared through compression moulding with varied fiber weight fractions, and characterized using tensile, flexural, and impact tests as per ASTM standards. Thermal stability was assessed through Thermogravimetric Analysis (TGA). The aim is to explore the potential of this green composite system as a sustainable alternative in biodegradable product development and contribute to the growing body of knowledge in natural fiber-based composites.

Natural fibers such as jute, flax, hemp, banana, and sisal are widely used as reinforcements due to their biodegradability, low cost, and favourable strength-to-weight ratio. Among these, sisal fiber stands out due to its high cellulose content (up to 70%) and excellent tensile properties. Ramesh et al.[1] reported that sisal fiber composites demonstrated significant improvements in tensile and flexural strengths when used with thermosetting and biodegradable matrices. Similarly, Fiore et al.[2] observed that sisal-reinforced bio-composites exhibit competitive mechanical performance comparable to some synthetic fiber systems, especially when properly surface-treated to enhance fiber–matrix adhesion. Starch, a naturally occurring polysaccharide, is one of the most abundantly available biopolymers and has been widely researched as a matrix material. Cornflour slurry is especially attractive for its film-forming properties and biodegradability. However, it suffers from poor mechanical properties and water sensitivity in its native form. According to Mali et al.[3], corn starch films plasticized with glycerol or water can achieve modest tensile strength and elongation, but reinforcement is necessary to improve structural performance. Averous et al.[4] emphasized that thermal degradation of thermoplastic starch occurs around 280–320°C, making it suitable for low to moderate temperature applications. John et al.[5] investigated the mechanical properties of sisal–polyester composites and reported notable improvements in tensile and flexural behaviour. When used with starch matrices, the performance depends on interfacial bonding and moisture uptake. Rosa et al.[6] demonstrated that the mechanical integrity of starch-based composites improved substantially with alkali-treated sisal fibers, which enhanced interfacial bonding. Satyanarayana et al.[7] reported that sisal composites begin to degrade thermally around 250°C, with improved stability when fibers are surface-modified. Similarly, Ng et al.[8] evaluated the thermal and dynamic mechanical analysis (DMA) of starch/sisal composites and confirmed that fiber reinforcement delayed the onset of thermal degradation and improved the storage modulus. Joseph et al.[9] demonstrated that alkali-treated sisal fibers significantly improved the tensile strength and thermal behaviour of polymer composites due to enhanced interfacial bonding. Herrera et al.[10] (2004) further emphasized the role of fiber orientation and surface treatment in improving the mechanical integrity of sisal-reinforced composites. Dole et al.[11] reported that native and plasticized starch films showed poor tensile strength, which could be significantly improved by incorporating fibers. Zhang et al.[12] elaborated on the processing and thermal behaviour of thermoplastic starch (TPS), highlighting its decomposition onset at ~280°C, which aligns with low-temperature processing requirements. Abdellaoui et al.[13] further demonstrated that the mechanical and thermal behaviour of sisal composites exceeded that of unreinforced biopolymer matrices. Mohanty et al.[14] emphasized that sisal–starch composites serve as viable green alternatives to synthetic fiber systems when optimized for compatibility. Sgriccia et al.[15] used SEM and TGA to correlate fiber surface morphology with composite behaviour, concluding that improved interfacial bonding leads to better load transfer and enhanced thermal stability.

Fig.1: Forest of Sisal plants as seen in the desert area

2. SPECIMEN PREPARATION

The composite specimens were formulated using natural sisal fibers as the reinforcing phase and cornflour as the biodegradable matrix. Prior to incorporation, the sisal fibers were cleaned, sun-dried, and cut to a uniform length of approximately 20 mm to ensure consistent dispersion within the matrix. The cornflour was used in its native form and mixed with water at a predetermined ratio to form a homogenous paste, which served as the matrix material. To enhance interfacial adhesion between the hydrophilic fiber and matrix, a small amount of glycerol was added as a plasticizer. The prepared fibers were gradually incorporated into the cornflour paste under continuous stirring to achieve uniform fiber distribution. The mixture was then poured into pre-designed molds and allowed to cure at ambient conditions followed by oven drying at 80°C to remove residual moisture and ensure dimensional stability. This formulation approach promotes sustainable, biodegradable composites suitable for low-load structural applications.

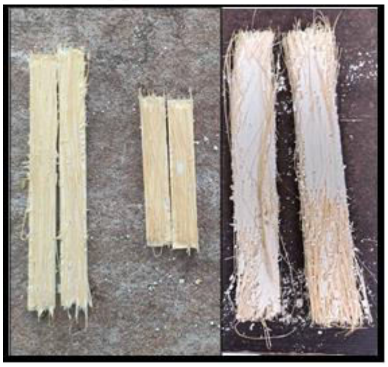

Fig. 2: Samples for Tensile, Flexural and Impact strength of Sisal/cornflour

3. MECHANICAL TESTING

3.1 Tensile test

Tensile properties of the sisal fiber-reinforced cornflour composites were evaluated in accordance with ASTM D638 using a universal testing machine (UTM) equipped with a 5 kN load cell. Dog-bone-shaped specimens were prepared with dimensions conforming to Type IV standards, ensuring uniform stress distribution during testing. The tests were conducted at room temperature under a constant crosshead speed of 5 mm/min. Each specimen was clamped securely to prevent slippage, and an extensometer was used to accurately measure elongation. For each fiber loading percentage (10%, 20%, and 30% by volume), a minimum of five specimens were tested to ensure statistical relevance. The tensile strength, Young's modulus, and elongation at break were calculated from the stress-strain curves. The results demonstrated a significant increase in tensile strength and stiffness with increasing fiber content, attributed to effective load transfer between the matrix and the alkali-treated sisal fibers. However, a slight reduction in elongation at break was observed at higher fiber loadings, indicating reduced ductility of the composites. Fig. 3 shows the Specimen Dimension for tensile test according to ASTM D638.

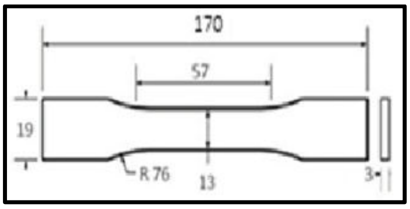

Fig.3: ASTM D638 Specimen Dimension for tensile test

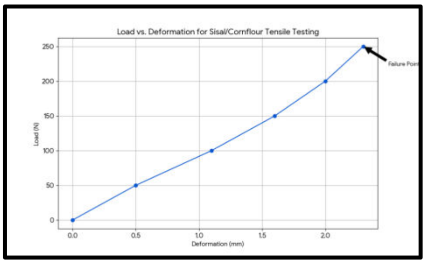

Fig.4: Load – Deformation Curve for Sisal/Cornflour composite under tensile loading

Fig. 4 represents the Load – Deformation Curve for Sisal/Cornflour composite which shows the tensile behavior of a sisal fiber-reinforced cornflour composite under increasing load. The X-axis (Deformation in mm) represents the elongation of the specimen as tensile force is applied. Y-axis (Load in N) indicates the force applied to the specimen during the test. The curve rises non-linearly, showing an initial linear region followed by a gradual curvature as the material nears failure. The load increases steadily with deformation, reaching a maximum load of approximately 250 N at around 2.3 mm deformation, which is marked as the Failure Point.This failure point represents the ultimate tensile strength (UTS) of the composite beyond this point, the material can no longer sustain load and fractures. The non-linear behavior suggests that while the material exhibits elastic characteristics initially, it begins to yield or undergo plastic deformation as the load increases. The absence of a sharp drop after the peak implies brittle fracture behavior is minimal, and the material undergoes some plastic deformation before breaking.

3.2 Flexural test:

Flexural properties of the sisal fiber-reinforced cornflour composites were evaluated in accordance with ASTM D790 using a three-point bending test configuration. Rectangular specimens of dimensions 80 mm × 12.7 mm × 3.2 mm were prepared and conditioned at ambient temperature prior to testing. Fig. 5 shows the Specimen Dimension for tensile test according to ASTM D790.

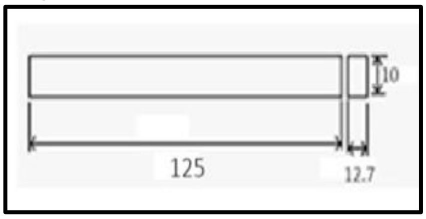

Fig.3: ASTM D790 Specimen Dimension for flexural test

The tests were performed on a universal testing machine with a span length of 64 mm and a crosshead speed of 2 mm/min, as recommended by the standard. The specimen was placed on two supports, and the load was applied at the midpoint to induce bending stress. For each fiber loading (10%, 20%, and 30% by volume), at least five specimens were tested to ensure reproducibility. The flexural strength and flexural modulus were calculated from the load-deflection curves. Results indicated that flexural strength increased with fiber content, with 30% fiber-reinforced specimens showing the highest load-bearing capacity. The improvement is attributed to enhanced fiber-matrix interaction and the effective stress distribution provided by the aligned natural fibers. However, excessive fiber loading beyond 30% may lead to agglomeration and void formation, which could adversely affect performance. Overall, the composites exhibited promising flexural behavior, demonstrating their potential for biodegradable structural and semi-structural applications. Fig.5: Load – Deformation Curve for Sisal/Cornflour composite under Flexural loading.

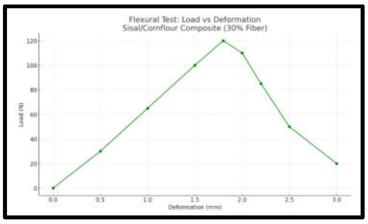

Fig.5: Load – Deformation Curve for Sisal/Cornflour composite under Flexural loading

Fig. 5 shows the Load – Deformation Curve for Sisal/Cornflour composite under Flexural loading in which the Elastic (nearly linear) region is from 0 to ≈1.5 mm where load rises almost linearly from 0 to ~100 N. Secant stiffness in this zone ≈ 65–67 N/mm (100 N / 1.5 mm ≈ 66.7 N/mm). Peak load appears to be at ~120 N at ≈1.8 mm deformation. This is the ultimate flexural load. After 1.8 mm the load drops to ~110 N at 2.0 mm, then more steeply to ~50 N at 2.5 mm and ~20 N at 3.0 mm. This descending branch indicates progressive damage i.e matrix cracking leading to fiber/matrix de-bonding and then fiber pull-out or rupture. The fact that it doesn't drop to zero immediately suggests some energy absorption (toughness) and pseudo-ductile behavior due to fiber bridging/pull-out. Ductility or toughness can be observed in the area under the curve (energy absorbed) which is appreciable; qualitatively, there's significant post-peak deformation before complete loss of capacity, which is favorable for damage tolerance.

3.3 Impact test

Impact strength is a critical mechanical property that determines a material's ability to absorb energy during fracture. The Izod impact test was conducted in accordance with ASTM D256 standards using a pendulum-type impact tester. Notched specimens of dimensions 63.5 mm × 12.7 mm × 3.2 mm were used. Fig. 3 shows the Specimen Dimension for tensile test according to ASTM D638.

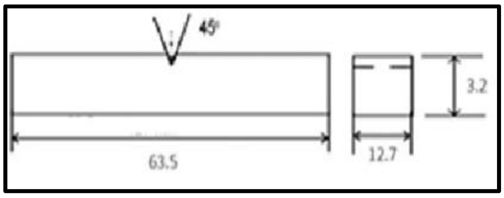

Fig.3: ASTM D256 Specimen Dimension for Impact test

The samples were rigidly clamped vertically with the notched side facing the pendulum. The energy absorbed by the composite before fracture was recorded to assess its toughness. Among all tested samples, composites with 35.2% fiber volume fraction exhibited the highest impact strength, suggesting an optimal interfacial bonding between sisal fibers and the corn flour matrix. Composites with lower fiber content showed insufficient reinforcement, while higher fiber content resulted in brittle failure due to poor matrix wetting and fiber agglomeration. Fig. 6 shows bar graph showing the variation of impact strength with different fiber volume fractions. The peak is observed at 30%, indicating optimal reinforcement.

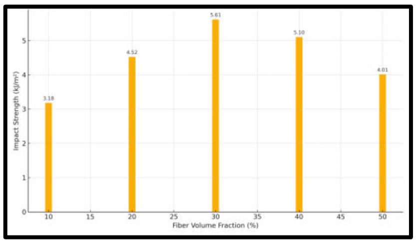

Fig. 6 shows bar graph showing the variation of impact strength with different fiber volume fractions. The peak is observed at 30%, indicating optimal reinforcement.

4. RESULT AND DISCUSSION

The mechanical performance of the fabricated sisal/cornflour composites was evaluated through tensile, flexural, and impact testing as per ASTM standards. The results reveal that the mechanical behavior of the composite is significantly influenced by the fiber volume fraction and interfacial bonding between the sisal fibers and cornflour matrix.

4.1 Tensile Properties

The tensile strength and Young's modulus of the composites increased with increasing fiber content up to an optimal level (typically around 30–40% by volume). Beyond this, a marginal reduction or plateau was observed, likely due to poor dispersion and increased fiber agglomeration which hinder stress transfer. The maximum tensile strength recorded was 28.19 MPa.

4.2 Flexural Behavior

The three-point bending test demonstrated that flexural strength and modulus also improved with increased fiber content. The load-deflection curves showed a more linear and brittle response for higher fiber ratios, indicating an enhancement in stiffness. The maximum flexural strength observed was 27.9 MPa. The improved performance can be credited to better stress distribution due to fiber bridging, although beyond optimal fiber content, the matrix continuity was compromised.

4.3 Impact Strength

Impact strength was evaluated using the Izod impact test. The results indicate that impact resistance increased with fiber addition up to a moderate volume fraction. The maximum energy absorption recorded was 12.405 kJ/m^2. The improved impact behavior is due to the energy dissipated through fiber pull-out and microcrack deflection mechanisms. However, excess fiber content led to poor matrix wetting and stress concentrations, reducing energy absorption capability.

5. CONCLUSIONS

Sisal fiber-reinforced cornflour-based composites were successfully fabricated using a compression molding technique, demonstrating the potential of biodegradable and eco-friendly composite systems.

Improved Mechanical Properties: The inclusion of sisal fiber significantly enhanced the tensile, flexural, and impact properties of the composites compared to the neat cornflour matrix. Mechanical performance improved with increasing fiber volume fraction up to an optimal level (~30–40%), beyond which a decline or plateau in properties was observed due to fiber agglomeration and poor interfacial adhesion.

Tensile and Flexural Strengths: The composite exhibited higher tensile and flexural strengths with fiber reinforcement, attributed to the high cellulose content and load-bearing capacity of sisal fibers.

Impact Resistance: The impact strength increased with moderate fiber loading, suggesting effective energy dissipation through fiber pull-out mechanisms. However, at higher fiber concentrations, the impact resistance decreased due to reduced matrix continuity. The results confirm that sisal/Cornflour composites are promising candidates for sustainable, biodegradable materials in non-structural applications, such as packaging, automotive interiors, and household products.

Further improvements in mechanical performance could be achieved by chemical treatment of fibers or hybridization with other natural or synthetic fibers to enhance bonding and durability.

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