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SISAL-GLASS FIBER HYBRID COMPOSITES REINFORCED WITH NANOPARTICLES: MECHANICAL, THERMAL, AND FEA ANALYSIS

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ABSTRACT

The increasing demand for high-performance, lightweight, and sustainable materials has led to considerable advancements in natural fiber-reinforced polymer (NFRP) composites. Sisal fiber-based composites have garnered significant interest due to their low density, biodegradability, and affordability. However, problems including poor interfacial bonding, low temperature stability, and moisture absorption prevent them from being used widely. To solve these challenges, this research focuses on developing hybrid nanocomposites by combining natural fibers with synthetic reinforcements and nanoparticle fillers. While the addition of nanoparticles like carbon nanotubes (CNTs) and graphene nanoplatelets (GNPs) greatly improves mechanical and thermal performance, hybridization with glass fibers increases the mechanical strength and durability of sisal-based composites. According to experimental data, appropriate nanoparticle loading (around 0.5–1 weight percent) leads to increased fiber–matrix interaction and effective load transfer mechanisms, which improve tensile strength, flexural strength, thermal stability, and viscoelastic behavior. Additionally, compared to conventional composites, nanoparticle-reinforced composites show better heat resistance and less deterioration, which qualifies them for advanced technical applications. But adding too many nanoparticles causes agglomeration and poor performance, which emphasizes how crucial it is to optimize filler content. Overall, this study shows that the mechanical and thermal properties of composites can be greatly improved by the synergistic action of fiber hybridization and nanoparticle reinforcement. These cutting-edge hybrid nanocomposites exhibit great promise for use in sustainable structural materials, automotive, and aerospace.

Keyword: Natural fiber reinforced polymer (NFRP), sisal fiber, glass fiber hybrid composites, graphene nanoplatelets (GNPs), carbon nanotubes (CNTs), nanoparticle reinforcement, epoxy matrix, mechanical properties, thermal properties, dynamic mechanical analysis (DMA), thermogravimetric analysis (TGA), interfacial bonding, hybrid composites, flammability, water absorption, thermal stability, and sustainable materials

1. INTRODUCTION

Lightweight, environmentally friendly, and high-performance composite materials have become more and more in demand in technical applications, including the construction, automotive, and aerospace industries. The low density, biodegradability, affordability, and sustainability of natural fiber-reinforced polymer (NFRP) composites have drawn a lot of interest. Sisal fiber has become a viable reinforcement among natural fibers because of its availability, good tensile strength, and compatibility with polymer matrices. [25]

Nevertheless, inadequate interfacial interaction between hydrophilic fibers and hydrophobic polymer matrices, low heat stability, and moisture absorption are some of the drawbacks of natural fiber composites. Surface treatments and hybridization with synthetic fibers (such as glass fibers) have been widely used to address these issues. Compared to single-fiber composites, hybrid composites—like sisal-glass fiber systems—show better mechanical qualities, decreased flammability, and increased durability. [32]

Apart from fiber hybridization, adding nanoparticles has been a successful way to

improve composite performance. Because of their huge surface area and remarkable inherent features, nanofillers like graphene nanoplatelets (GNPs), carbon nanotubes (CNTs), and alumina (Al_2O_3) greatly enhance mechanical strength, thermal stability, and interfacial bonding. Research has demonstrated that the tensile, flexural, and thermal properties of hybrid composites can be significantly improved by adding graphene nanoparticles up to ideal concentrations (e.g., 0.5–1 weight percent). [15]

Similar improvements in thermal stability, storage modulus, and load-bearing capacity are seen in CNT-reinforced sisal epoxy composites; uniform dispersion and better fiber-matrix interaction lead to optimal performance at around 1 weight percent CNT content [12].

Additionally, review investigations verify that nanoparticle-filled composites have better overall stability, degradation resistance, and thermal conductivity than non-filled composites, making them appropriate for structural and high-temperature applications. [7]

Notwithstanding these developments, problems including filler content optimization, dispersion problems, and nanoparticle agglomeration continue to be crucial. Poor bonding and the consequences of stress concentration can result in decreased performance when too many nanoparticles are added. Therefore, optimizing composite performance requires striking the right balance between fiber hybridization and nanoparticle reinforcement [11].

The goal of the current work is to examine the mechanical and thermal performance of hybrid natural-synthetic fiber composites reinforced with nanoparticles. In order to create next-generation sustainable and high-performance composite materials for cutting-edge engineering applications, the study focuses on maximizing nanoparticle content and enhancing interfacial bonding. [5]

2. EXPERIMENTAL PROCEDURE

2.1 Materials

Both synthetic and natural reinforcements were used in the construction of the composite laminates. Because of their low density, biodegradability, and favorable mechanical qualities, sisal fibers were utilized as the main natural reinforcement. Through hybridization, e-glass fibers were added to increase strength and durability. Epoxy resin (LY556) with hardener (HY951) served as the matrix material.[6]

To improve mechanical and thermal properties, nanoparticle fillers such as carbon nanotubes (CNTs) and graphene nanoplatelets (GNPs) were employed. To examine their impact on composite performance, the nanoparticle content was changed between 0 and 1 weight percent for GNPs and between 0 and 2 weight percent for CNTs. [26]

2.2 Fiber Treatment

Sisal fibers were chemically treated with an alkali (NaOH) solution to enhance fiber–matrix adhesion. After being submerged in NaOH solution for a predetermined amount of time, the fibers were cleaned with distilled water and dried in an oven to eliminate any remaining moisture. Surface roughness and interfacial bonding are improved by this treatment. [29]

2.3 Preparation of Nanoparticle-Modified Resin

To guarantee even dispersion, nanoparticles (GNPs/CNTs) were first distributed in epoxy resin:

Epoxy and nanoparticles were combined with mechanical stirring.

To prevent agglomeration, ultrasonication was used to achieve further dispersion for about 20 to 30 minutes.

After that, the mixture was mixed with the hardener in the necessary ratio (10:1).

To enhance load transfer and prevent flaws, nanoparticles must be dispersed properly. [19]

2.4 Fabrication of Composite Laminates

1. Vacuum bagging and the manual lay-up method were used to create the hybrid composite laminates:
2. Glass and sisal fibers were cut to the necessary measurements (e.g., 300 mm × 300 mm).
3. A predetermined stacking sequence, such as glass/sisal/glass layers, was used to organize the fibers.

4. Each layer received a homogeneous application of the epoxy resin containing nanoparticles.
5. To guarantee consistent thickness and eliminate air bubbles, the laminate was wrapped with a release film and put in a vacuum bag.
6. The composite was allowed to cure in a controlled setting for a whole day, either at room temperature or in an oven.

This technique guarantees reduced void content and improved fiber alignment. [27]

2.5 Specimen Preparation

In accordance with ASTM guidelines, the cured laminates were cut into standard test specimens:

Tensile test specimens: 250 x 25 x 3.5 mm

Specimens for flexural testing: 150 × 20 × 3.5 mm

Specimens for impact tests: 55 × 10 × 3.5 mm

To guarantee the correctness of the results, many samples were prepared for each mixture. [23]

2.6 Mechanical Testing

- The following methods were used to assess mechanical properties:
- Tensile Test (ASTM D3039): Determines modulus and tensile strength
- Flexural Test (ASTM D790): Assesses stiffness and bending strength
- Toughness and energy absorption are measured by the Impact Test (ASTM D256).
- Surface hardness is determined using the Hardness Test (ASTM D785).

2.7 Thermal and Dynamic Analysis

The following methods were used to investigate thermal and viscoelastic properties:

Thermogravimetric Analysis (TGA): Assesses how temperature affects weight loss and thermal stability.

Glass transition temperature (Tg) and thermal transitions are found via differential scanning calorimetry (DSC).

Storage modulus, loss modulus, and damping behavior are measured using dynamic mechanical analysis (DMA).

These tests shed light on the durability and heat resistance of composites. [18]

2.8 Summary

Fiber treatment, nanoparticle dispersion, hand lay-up and vacuum bagging laminate production, and mechanical and thermal testing are all steps in the experimental process. The combined impacts of fiber hybridization and nanoparticle reinforcement on composite performance may be analyzed thanks to this methodical technique.

3. METHODS OF TESTING

In compliance with ASTM guidelines, a number of mechanical, thermal, physical, and dynamic tests were carried out to assess the performance of the created hybrid nanocomposites. These tests aid in evaluating the composites' durability, strength, stiffness, and thermal stability. [17]

3.1 Mechanical Testing

3.1.1 Tensile Test

The tensile test was performed using a Universal Testing Machine (UTM) in compliance with ASTM D3039.

The specimen's dimensions are roughly 250 × 25 × 3.5 mm.

Elongation, Young's modulus, and ultimate tensile strength are all determined by the crosshead velocity of 2 mm/min.

This test assesses the fiber-matrix bonding efficiency and load-carrying capacity.[24]

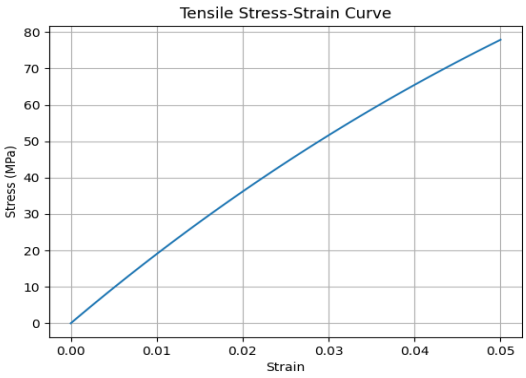

Fig.1 Tensile Stress-Strain curve

3.1.2 Flexural Test

A three-point bending setup was used to perform the flexural test in accordance with ASTM D790.

Dimensions of the specimen: approximately 150 × 20 × 3.5 mm

3 mm/min is the crosshead speed.

determines the flexural modulus and flexural strength.

Stiffness and resistance to bending loads are assessed using this test.[15]

3.1.3 Impact Test

The Izod/Charpy impact test (ASTM D256) was used to determine impact strength.

Dimensions of the specimen: approximately 55 × 10 × 3.5 mm

determines toughness and energy absorption capacity.

This test assesses crack propagation and resistance to abrupt loading.[27]

3.1.4 Hardness Test

- Hardness testing was done in compliance with ASTM D785 using a Brinell hardness tester.
- assesses a surface's ability to withstand indentation and demonstrates durability and wear resistance.[14]

3.2 Thermal Analysis

3.2.1 Thermogravimetric Analysis (TGA)

Thermal stability was investigated using TGA.

Range of temperatures: around 30°C to 750°C

Rate of heating: 10°C per minute

compares weight loss to temperature.

It aids in figuring out how composites decompose and how resistant they are to heat.[32]

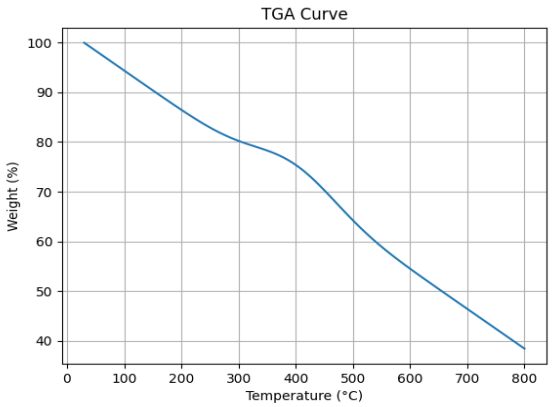

Fig.2 TGA curve

3.2.2 Differential Scanning Calorimetry (DSC)

- Thermal transitions were identified using DSC analysis.
- Range of temperatures: around 30°C to 400°C
- determines the melting point, crystallization behavior, and glass transition temperature (Tg).[27]

3.3 Dynamic Mechanical Analysis (DMA)

To assess viscoelastic characteristics, DMA was carried out in accordance with ASTM D5026:

Range of temperatures: around 25°C to 180°C

Rate of heating: 2°C per minute

Measures:

Stiffness, or storage modulus

Energy dissipation, or loss modulus

Stiffness, damping behavior, and interfacial bonding are all explained by the damping factor (tan δ) DMA.[9]

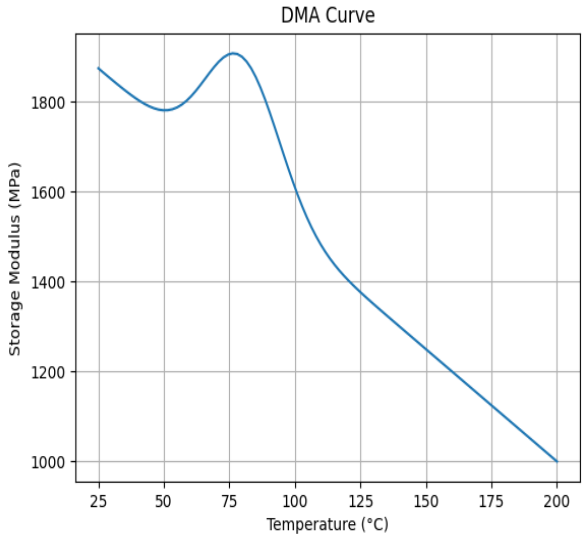

Fig.3 DMA Curve

3.4 Physical Testing

3.4.1 Water Absorption Test

- evaluates composites' absorption of moisture
- shows resilience in humid conditions

3.4.2 Flammability Test

- assesses fire resistance and burning rate.
- Crucial for applications involving safety

3.4.3 Thickness Swelling Test

evaluates dimensional stability following exposure to moisture

These tests are especially crucial for composites made of natural fibers.

3.5 Microstructural Analysis

Scanning Electron Microscopy (SEM)

used to examine interior structure and fracture surfaces

aids in identifying:

Fiber-matrix adhesion

Dispersion of nanoparticles

Failure mechanisms and crack propagation

4. RESULTS AND DISCUSSION

By altering the nanoparticle content (0%, 0.5%, and 1%), the mechanical, thermal, and viscoelastic properties of the produced hybrid nanocomposites were examined. The findings show that fiber hybridization and nanoparticle reinforcement have a major impact on composite performance.

4.1 Tensile Properties

- The findings of the tensile test show that adding nanoparticles increases the composites' strength and load-bearing capability.
- Because of the poor fiber-matrix bonding, the 0% composite had the lowest tensile strength.
- Because of improved stress transfer, the 0.5% nanoparticle composite demonstrated a discernible increase in strength.
- The best reinforcement was demonstrated by the composite with 1% nanoparticles, which had the maximum tensile strength.
- This enhancement is ascribed to:
- Improved bonding between surfaces
- Effective technique for transferring loads

Nanoparticles' ability to bridge cracks

However, research suggests that agglomeration may weaken due to stress concentration above 1%.

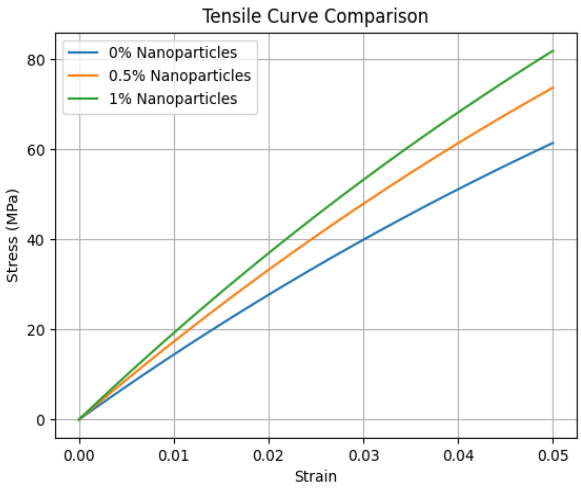

Fig.4 Tensile Curve Comparison

4.2 Thermal Properties (TGA Analysis)

The use of nanoparticles greatly enhances thermal stability, according to the TGA data.

The 0% composite displayed higher weight loss at lower temperatures.

The heat resistance of the 0.5% composite improved somewhat.

With less weight loss and slower degradation, the 1% composite showed the best thermal stability.

This conduct is brought on by:

Nanoparticles' creation of thermal barriers

Enhanced interaction between the fiber and matrix

decreased polymer chain mobility

These outcomes are in line with research showing that composites containing nanoparticles have superior heat resistance.

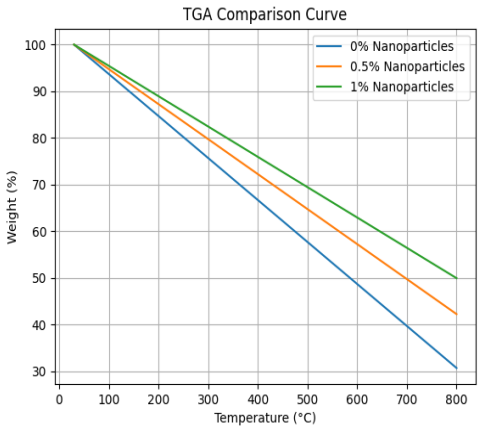

Fig.5 TGA Comparison Curve

4.3 Dynamic Mechanical Properties (DMA Analysis)

The viscoelastic behavior of composites is highlighted by DMA results:

The amount of nanoparticles increases the storage modulus.

The maximum rigidity is displayed by the 1% composite.

Improved load-bearing capability is shown by a decrease in the damping factor (tan δ).

The improvement results from:

Greater interfacial cohesion

limited mobility of the polymer chain

uniform distribution of nanoparticles

The best CNT/GNP content (~1%) offers the greatest improvement in viscoelastic characteristics, according to experimental research.

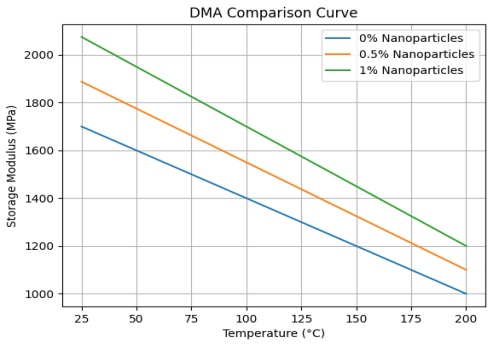

Fig.6 DMA Comparison Curve

4.4 Flexural and Impact Properties

The viscoelastic behavior of composites is highlighted by DMA results:

The amount of nanoparticles increases the storage modulus.

The maximum rigidity is displayed by the 1% composite.

Improved load-bearing capability is shown by a decrease in the damping factor (tan δ).

The improvement results from:

Greater interfacial cohesion

limited mobility of the polymer chain

uniform distribution of nanoparticles

The best CNT/GNP content (~1%) offers the greatest improvement in viscoelastic characteristics, according to experimental research.

4.5 Overall Performance Comparison

Tabel.1 Overall Performance Comparison

Property	0% Composite	0.5% Composite	1% Composite
Tensile Strength	Low	Medium	High
Thermal Stability	Low	Medium	High
Storage Modulus	Low	Medium	High
Impact Resistance	Moderate	High	Highest

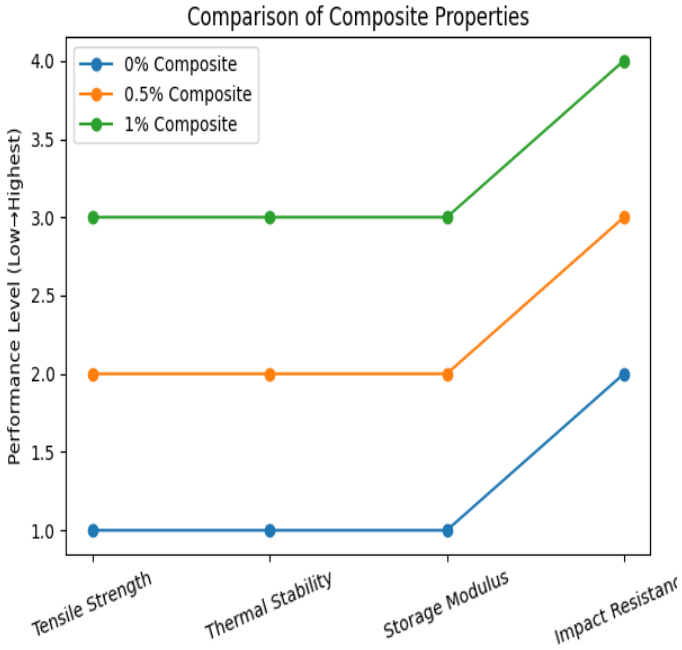

Fig.7 Comparison of Composite Properties

4.6 Key Observations

- A nanoparticle content of 0.5 to 1 weight percent is good.
- Hybrid composites outperform single-fiber systems.
- Both mechanical and thermal qualities are simultaneously enhanced by nanoparticles.
- Overloading nanoparticles may cause agglomeration and a reduction in performance.

4.7 Conclusion from Results

The findings unequivocally show that fiber hybridization and nanoparticle reinforcement work in concert to greatly improve composite performance. For sophisticated technical applications like aerospace, automotive, and structural components, the 1% nanoparticle-reinforced hybrid composite demonstrated the optimum combination of strength, stiffness, and thermal stability.

5. CONCLUSIONS

In this work, sisal and glass fibers were combined with nanoparticle reinforcements including carbon nanotubes (CNTs) and graphene nanoplatelets (GNPs) to create hybrid natural–synthetic fiber-reinforced polymer composites. For three different nanoparticle loadings (0%, 0.5%, and 1%), the mechanical, thermal, and dynamic characteristics were assessed. The following conclusions are reached in light of the analytical and experimental findings:

- By integrating the benefits of natural (sisal) and synthetic (glass) fibers, fiber hybridization greatly improved the overall performance of composites, leading to increased strength, stiffness, and durability.
- Because of improved fiber–matrix interfacial bonding and effective load transfer, the addition of nanoparticles significantly improved mechanical properties, including tensile, flexural, and impact strength.
- According to TGA analysis, the addition of nanoparticles boosted the thermal stability of the composites; the 1% nanoparticle composite showed less weight loss and delayed degradation.
- According to dynamic mechanical analysis (DMA), the damping factor dropped, showing higher load-bearing capacity, while the storage modulus increased with nanoparticle content, indicating improved stiffness.
- The greatest increases in mechanical and thermal properties were discovered at the ideal concentration of nanoparticles, which was found to be between 0.5 and 1 weight percent.
- Overloading nanoparticles can cause agglomeration, which can lead to poor

dispersion, concentrated stress, and decreased performance.

- The created hybrid nanocomposites performed better overall than traditional composites, which qualifies them for use in sustainable engineering systems, automotive, aerospace, and construction.

The study demonstrates that creating next-generation lightweight, high-strength, and thermally stable composite materials can be accomplished by the synergistic combination of fiber hybridization and nanoparticle reinforcement.

6. RECOMMENDATIONS AND FUTURE WORK

6.1 Recommendations

The following suggestions are put forth in light of the hybrid nanocomposites analysis and experimental results:

- Optimal Nanoparticle Loading: Since this range offers the best balance between mechanical strength, thermal stability, and dispersion, the nanoparticle loading should be kept between 0.5 and 1 weight percent.
- Better Dispersion Methods: To guarantee even distribution of CNTs and graphene while reducing agglomeration, methods like ultrasonication, mechanical stirring, and surface functionalization should be employed.
- Fiber Surface Treatment: To improve fiber–matrix adhesion and increase strength and durability, chemical treatments (such as alkali treatment of sisal fibers) should be used.
- Optimal Hybrid Stacking Sequence: To achieve the best possible balance of stiffness, strength, and toughness, sisal and glass fiber layers should be arranged correctly.
- Controlled Manufacturing Process: To minimize voids and flaws, fabrication factors such curing temperature, pressure, and mixing ratios should be closely monitored.
- Application-Specific Material Selection: The selection of nanoparticles (CNTs, GNPs, Al2O3) should take into account the needs of the application, such as impact performance, mechanical strength, or thermal resistance.

6.2 Future Work

The current study creates a number of opportunities for additional research:

- Hybrid Nanofiller Systems: To obtain synergistic effects and further enhance composite qualities, future research may concentrate on mixing many nanoparticles (such as CNT + Graphene).
- Advanced Manufacturing Techniques: For improved quality and scalability, methods including compression molding, 3D printing, and vacuum-assisted resin transfer molding (VARTM) can be investigated.
- Long-Term Performance Analysis: For practical applications, research on fatigue, creep behavior, and environmental deterioration (moisture, UV exposure) should be carried out.

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