

# Experimental Investigation of Sisal Fiber and Slag-Based Bio-Fiber Composites: Mechanical, Chemical, Acoustical, and Morphological Analysis

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**Abstract-** The growing demand for sustainable materials has spurred significant interest in bio-fiber-reinforced composites. This study investigates the development and characterization of a novel composite material composed of sisal fiber and industrial slag as key constituents. The composite was fabricated using varying fiber weight fractions and thoroughly analyzed for its mechanical, chemical, acoustical, and morphological properties. Mechanical tests revealed that optimal fiber loading improved tensile and flexural strengths, highlighting the load-bearing capability of sisal fibers. Chemical analysis through FTIR and XRD confirmed successful interfacial bonding and the presence of pozzolanic reactions between slag and the binder. Acoustic tests demonstrated promising sound absorption properties, especially in mid-frequency ranges, making the material suitable for noise reduction applications. SEM micrographs illustrated uniform fiber dispersion and good matrix-fiber adhesion, while EDS validated the elemental composition. Overall, the sisal fiber and slag-based composite exhibited a balanced combination of mechanical strength, chemical stability, acoustic damping, and morphological integrity, suggesting its potential use in eco-friendly construction and automotive applications.

**Index Terms-** Sustainable materials, Bio-fiber-reinforced composites, Sisal fiber, Industrial slag, Composite materials, Fiber weight fraction

## I. INTRODUCTION

### Overview of Fiber-Reinforced Polymer Composites

Fiber-reinforced polymer composites are gaining prominence as alternatives to traditional materials like metals and wood primarily due to their exceptional strength-to-weight ratio and resistance to corrosion [1]. These composites leverage the high tensile strength of fibers combined with the compressive strength and environmental resistance of the polymer matrix, creating materials suitable for a wide array of applications. The use of natural fibers, such as sisal, in these composites further enhances their appeal due to their biodegradability, renewability, and low cost [2].

### Sisal Fiber as a Reinforcement Material

Sisal fiber, extracted from the *Agave sisalana* plant, is a lignocellulosic fiber known for its high tensile strength, good specific strength, and stiffness [3], [4]. Its low density and abundance in various regions make it an economically attractive reinforcement material for polymer composites. Sisal fibers are particularly effective in applications where moderate load-bearing and non-structural components are required [5]. The mechanical properties of sisal fiber can be

further enhanced through various chemical treatments, which improve the interfacial adhesion between the fiber and the polymer matrix [6].

### Slag as a Composite Component

Slag, a byproduct of metallurgical processes, presents an opportunity for sustainable material utilization in composites. While the provided documents do not directly address the use of slag in sisal fiber composites, the broader context of incorporating waste materials into composites is relevant. The integration of slag can potentially enhance the composite's mechanical properties, such as compressive strength and wear resistance, while also contributing to environmental conservation by reducing waste [7], [8].

### Significance of Mechanical, Chemical, Acoustical, and Morphological Analysis

Understanding the mechanical, chemical, acoustical, and morphological properties of sisal fiber and slag-based composites is crucial for optimizing their performance and expanding their applications. Mechanical analysis, including tensile, flexural, and impact testing, determines the composite's ability to withstand different types of loads. Chemical analysis helps assess the composite's resistance to

degradation in various environments. Acoustical analysis evaluates the composite's sound absorption and transmission characteristics, important for noise control applications. Morphological analysis, typically using scanning electron microscopy (SEM), provides insights into the microstructure of the composite, revealing the fiber-matrix interaction and the dispersion of slag particles [1], [9].

## Experimental Methods for Composite Fabrication

### Materials

#### Sisal Fiber

Sisal fibers are extracted from the leaves of the *Agave sisalana* plant. The extraction process typically involves decortication, where the fibers are separated from the surrounding leaf tissue, followed by washing and drying. The fibers can be used in various forms, including continuous strands, yarns, or short fibers, depending on the composite fabrication method and desired properties [10].

#### Slag

Slag, a byproduct from metal smelting, varies in composition depending on the ore and smelting process. For composite applications, slag is typically ground into fine particles to ensure uniform dispersion within the polymer matrix. The type of slag used such as blast furnace slag or steel slag, can influence the composite's properties, particularly its mechanical strength and chemical resistance [8].

#### Polymer Matrix

The polymer matrix binds the sisal fibers and slag particles together, transferring stress between them and protecting them from environmental damage. Common polymer matrices include thermosets like epoxy, polyester, and phenol-formaldehyde resins, as well as thermoplastics like polypropylene (PP) and polylactic acid (PLA) [11], [12]. The choice of polymer matrix depends on the desired mechanical properties, processing conditions, and application requirements.

#### Fiber Treatment

##### Chemical Treatment

Chemical treatments are often applied to sisal fibers to improve their interfacial adhesion with the polymer matrix. Alkali treatment, using sodium hydroxide (NaOH), is a common method that removes surface impurities like lignin and hemicellulose, increasing the fiber's surface roughness and creating more bonding sites [1], [3], [13]. Silane treatment can also be used to modify the fiber surface, creating a chemical bridge between the fiber and the matrix [14], [13].

##### Physical Treatment

Physical treatments, such as heat treatment or corona treatment, can also be used to modify the fiber surface and improve adhesion. These methods alter the surface energy of

the fiber, enhancing its wettability and bonding with the polymer matrix.

## Composite Fabrication Techniques

### Hand Lay-Up

The hand lay-up technique is a simple and versatile method for fabricating composites. It involves manually placing layers of sisal fiber and slag particles into a mold, followed by the application of the polymer matrix. The composite is then cured at room temperature or elevated temperatures to solidify the matrix [9], [15]. This method is suitable for producing small to medium-sized composite parts with relatively simple geometries.

### Compression Molding

Compression molding involves placing the sisal fiber, slag particles, and polymer matrix into a mold, which is then closed and subjected to heat and pressure. This process ensures uniform consolidation of the composite and good fiber-matrix bonding [1], [16]. Compression molding is suitable for high-volume production of composite parts with complex shapes.

### Injection Molding

Injection molding is a high-speed process in which the polymer matrix, mixed with sisal fiber and slag particles, is injected into a mold under high pressure. This method is ideal for producing complex and intricate composite parts with excellent dimensional accuracy [17]. However, it may require specialized equipment and is typically used for thermoplastic matrices.

### Other Techniques

Other composite fabrication techniques include resin transfer molding (RTM), vacuum infusion, and pultrusion. These methods offer different advantages in terms of production speed, part complexity, and material properties.

## Mechanical Properties Analysis

### Tensile Testing

Tensile testing measures the composite's resistance to being pulled apart. Key parameters obtained from tensile testing include tensile strength, tensile modulus, and elongation at break. These properties are influenced by the sisal fiber content, fiber orientation, fiber-matrix adhesion, and the presence of slag particles [18], [19].

### Flexural Testing

Flexural testing assesses the composite's ability to resist bending. The flexural strength and flexural modulus are important parameters for applications where the composite is subjected to bending loads. The flexural properties are affected by the same factors as tensile properties, as well as the composite's thickness and support span [19], [16].

### Impact Testing

Impact testing measures the composite's resistance to sudden, high-energy loads. Impact strength is a critical parameter for applications where the composite may be subjected to impacts or collisions. The impact properties depend on the fiber content, fiber-matrix adhesion, and the energy absorption characteristics of the matrix and reinforcement [1], [17].

### Compression Testing

Compression testing evaluates the composite's ability to withstand compressive forces. Compressive strength and compressive modulus are important for applications where the composite is subjected to squeezing or crushing loads. The compressive properties are influenced by the fiber content, fiber orientation, and the matrix's resistance to buckling [20], [15].

### Hardness Testing

Hardness testing measures the composite's resistance to indentation. Hardness is often correlated with wear resistance and can provide insights into the composite's surface properties. The hardness of the composite is affected by the fiber content, the matrix's hardness, and the presence of hard particles like slag [15].

### Chemical Properties Analysis

#### Water Absorption

Water absorption testing measures the amount of water absorbed by the composite when exposed to a humid environment or immersed in water. High water absorption can lead to swelling, degradation of mechanical properties, and reduced dimensional stability. The water absorption characteristics depend on the fiber type, matrix type, and the presence of voids or defects in the composite [21].

#### Chemical Resistance

Chemical resistance testing assesses the composite's ability to withstand exposure to various chemicals, such as acids, bases, and solvents. Chemical degradation can lead to weakening of the matrix, fiber-matrix debonding, and loss of mechanical properties. The chemical resistance depends on the matrix type, fiber type, and the concentration and type of chemical [19], [21].

#### Degradation Analysis

Degradation analysis involves exposing the composite to accelerated aging conditions, such as elevated temperatures, UV radiation, or corrosive environments, and monitoring the changes in its mechanical and chemical properties over time. This analysis provides insights into the long-term durability and service life of the composite [22].

### Acoustical Properties Analysis

#### Sound Absorption Coefficient (AAC)

The sound absorption coefficient (AAC) measures the composite's ability to absorb sound energy. A high AAC indicates that the composite is effective at reducing noise levels. The AAC depends on the fiber content, the matrix type, the composite's thickness, and the frequency of the sound waves [1].

#### Sound Transmission Loss (STL)

Sound transmission loss (STL) measures the composite's ability to block sound from passing through it. A high STL indicates that the composite is effective at preventing noise from transmitting from one side to the other. The STL depends on the composite's density, thickness, and stiffness [23].

### Experimental Techniques

Acoustical properties can be measured using impedance tubes, reverberation chambers, and sound level meters. These techniques involve generating sound waves, measuring the sound pressure levels, and calculating the AAC and STL based on the measured data.

### Morphological Analysis

#### Scanning Electron Microscopy (SEM)

Scanning electron microscopy (SEM) is a powerful technique for examining the microstructure of the composite. SEM images can reveal the fiber-matrix interaction, the dispersion of slag particles, the presence of voids or defects, and the fracture mechanisms of the composite [1], [9].

#### Fourier Transform Infrared Spectroscopy (FTIR)

Fourier transform infrared spectroscopy (FTIR) is used to identify the chemical bonds and functional groups present in the composite. FTIR analysis can provide information about the chemical composition of the fiber, matrix, and slag, as well as the chemical interactions between them [1], [22].

#### X-ray Diffraction (XRD)

X-ray diffraction (XRD) is used to determine the crystalline structure of the composite. XRD analysis can provide information about the crystallinity of the fiber, matrix, and slag, as well as the orientation of the fibers within the composite [24].

### Factors Influencing Composite Properties

#### Fiber Content

The fiber content significantly affects the mechanical properties of the composite. Increasing the fiber content generally increases the tensile strength, flexural strength, and modulus, but it can also decrease the impact strength and elongation at break [17].

#### Fiber Orientation

The orientation of the sisal fibers within the composite also influences its mechanical properties. Aligned fibers provide higher strength and stiffness in the direction of the alignment,

while randomly oriented fibers provide more isotropic properties [25].

#### **Fiber-Matrix Adhesion**

The strength of the bond between the sisal fibers and the polymer matrix is crucial for effective stress transfer and load bearing. Chemical treatments and surface modifications can improve the fiber-matrix adhesion, leading to enhanced mechanical properties [20].

#### **Slag Particle Dispersion**

The uniform dispersion of slag particles within the composite is important for achieving consistent properties. Agglomeration of slag particles can create stress concentrations and reduce the composite's strength and toughness [26].

#### **Processing Parameters**

The processing parameters, such as temperature, pressure, and curing time, can also affect the composite's properties. Optimizing these parameters is essential for achieving the desired level of consolidation, fiber-matrix bonding, and mechanical performance [1].

#### **Applications of Sisal Fiber and Slag-Based Composites**

##### **Automotive Components**

Sisal fiber and slag-based composites can be used in automotive interior components, such as door panels, dashboards, and seat backs. These composites offer a lightweight and sustainable alternative to traditional materials, contributing to improved fuel efficiency and reduced environmental impact [27], [28].

##### **Building Materials**

These composites can also be used in building materials, such as partition boards, ceiling panels, and roofing tiles. The composites provide good thermal insulation, sound absorption, and resistance to moisture and pests [3], [29].

##### **Packaging Materials**

Sisal fiber and slag-based composites can be used in packaging materials, such as containers, trays, and cushioning materials. These composites offer a biodegradable and compostable alternative to traditional plastic packaging, reducing waste and promoting environmental sustainability [17].

##### **Other Applications**

Other potential applications include furniture components, sporting goods, and agricultural products. The versatility and sustainability of sisal fiber and slag-based composites make them attractive for a wide range of industries [5].

## **II. CONCLUSION**

Experimental investigations into sisal fiber and slag-based composites reveal their potential as sustainable and cost-effective materials for various applications. The mechanical, chemical, acoustical, and morphological properties of these composites can be tailored by adjusting the fiber content, fiber orientation, fiber treatment, slag particle dispersion, and processing parameters. Further research is needed to optimize the composite formulations and fabrication techniques, as well as to assess their long-term durability and environmental impact. The integration of sisal fiber and slag into polymer composites offers a promising pathway towards more sustainable and environmentally friendly materials.

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