An experimental analysis of the Hardness characteristics of Sisal fiber, S-Glass fiber, and Nano Alumina reinforced Polymer Matrix Composites

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Abstract: A composite is a heterogeneous material system consisting of two or more distinct phases matrix and reinforcement that are mechanically bonded at their interface. This combination enhances the overall mechanical, thermal, and chemical properties beyond those of the individual constituents. The present study focuses on the fabrication of epoxy-based composites reinforced with Sisal fiber and S-glass fiber. Prior to fabrication, the sisal fibers were subjected to a 5% NaOH alkaline treatment to improve surface adhesion and interfacial bonding. During composite preparation, Nano Alumina (Al_2O_3) was incorporated at varying weight fractions of 1%, 1.5%, and 2% of the total composite weight. The fabricated composite specimens were then machined using a water jet process and tested for Shore D hardness in accordance with ASTM D2240 standards. The experimental results revealed that alkali treatment of fibers and the addition of Nano Alumina fillers led to a notable enhancement in the hardness of the developed hybrid composites.

Index Term: Sisal, S-glass, Nano Alumina (Al_2O_3), Epoxy resin, hand layup process, Hardness.

I. Introduction

In recent years, composite materials have become one of the most significant developments in materials science and engineering, owing to their ability to combine the advantageous properties of different constituents into a single structure. A composite material is defined as a system composed of two or more distinct phases matrix and reinforcement mechanically bonded at the interface, resulting in improved mechanical, thermal, and chemical properties compared to the individual materials (Chawla, 2012). Among various categories of composites, polymer matrix composites (PMCs) have gained immense popularity because of their lightweight nature, high corrosion resistance, and ease of processing (Callister & Rethwisch, 2020).

The global interest in eco-friendly and sustainable materials has encouraged the replacement of synthetic fibers with natural fibers such as jute, sisal, coir, hemp, and flax, which are renewable, biodegradable, and cost-effective (Mohanty, Misra, & Drzal, 2005). Sisal fiber, obtained from the leaves of *Agave sisalana*, is recognized for its high tensile strength, moderate stiffness, and excellent adhesion properties, making it a suitable reinforcement for polymer composites (Satyanarayana et al., 2007). However, the hydrophilic nature of sisal leads to poor compatibility with hydrophobic polymer matrices, which limits its mechanical performance. To overcome this issue, chemical surface modifications, particularly alkaline (NaOH) treatment, are widely adopted to remove waxes, lignin, and hemicellulose from the fiber surface, thus improving surface roughness and fiber–matrix interfacial bonding (Kabir et al., 2012).

Furthermore, the integration of nano fillers into polymer composites has been shown to substantially enhance mechanical, thermal, and tribological properties (Hussain, Hojjati, Okamoto, & Gorga, 2006). Among various nanofillers, Nano Alumina (Al_2O_3) has attracted considerable attention because of its high hardness, excellent thermal stability, and chemical inertness (John & Nair, 2002). When uniformly dispersed in the polymer matrix, Nano Alumina can improve load transfer efficiency, interfacial adhesion, and overall composite hardness and wear resistance (Ramesh, 2016). Therefore, the combination of natural fibers (Sisal), synthetic fibers (S-glass), and nano-scale ceramic fillers (Al_2O_3) provides a hybrid composite system with enhanced performance characteristics suitable for diverse engineering applications. This approach supports the development of sustainable, lightweight, and high-performance materials that align with modern environmental and industrial requirements.

II. Objectives

Studies on Hardness test of Chemically Treated Sisal Fiber/S-Glass/ Nano Alumina (Al_2O_3) Reinforced Hybrid PMCs is our main objective of this research. The study included following tasks.

- To fabricate hybrid polymer matrix composites reinforced with Sisal fiber and S-glass fiber using epoxy resin as the matrix.
- To chemically treat sisal fibers with 5% NaOH solution to enhance fiber–matrix interfacial bonding.
- To incorporate Nano Alumina (Al_2O_3) into the composites at varying weight percentages of 1%, 1.5%, and 2%.
- To machine the composite specimens using water jet machining in accordance with standard sample dimensions.
- To evaluate the hardness behaviour of the fabricated composites using the Shore D hardness test (ASTM D2240).
- To analyze the effect of alkali treatment and Nano Alumina addition on the hardness performance of the composites

III. LITERATURE SUMMERY

The review of past research indicates that natural fiber reinforced polymer composites (NFRPCs) have gained remarkable attention as environmentally friendly materials capable of replacing traditional synthetic composites in various structural and industrial applications. Among these natural fibers, sisal fiber has been widely recognized for its high tensile strength, renewability, low density, and biodegradability (Satyanarayana, Arizaga, & Wypych, 2007). However, its hydrophilic nature leads to poor adhesion with hydrophobic polymer matrices, resulting in weak interfacial bonding and reduced mechanical performance (Kabir, Wang, Lau, & Cardona, 2012). To improve the fiber–matrix compatibility, researchers have implemented various chemical surface treatments, such as alkaline (NaOH) treatment, which effectively removes surface impurities like lignin, waxes, and hemicellulose. This process increases surface roughness and enhances interfacial adhesion between the fiber and matrix (Mohanty, Misra, & Drzal, 2005; Kabir et al., 2012). The introduction of hybrid composites, which combine natural fibers (e.g., sisal) with synthetic fibers (e.g., S-glass), has shown significant improvement in mechanical properties. Such hybridization results in a balance between the strength and stiffness of synthetic fibers and the lightweight, biodegradable characteristics of natural fibers (Ramesh, 2016). Studies on sisal–glass hybrids have demonstrated notable enhancements in tensile, flexural, and impact strength compared to single-fiber composites (Atmakuri, Reddy, & Samal, 2020). Recent advances in nanotechnology have introduced nanofillers as an additional reinforcement phase to improve the mechanical, thermal, and tribological performance of fiber-reinforced composites (Hussain, Hojjati, Okamoto, & Gorga, 2006). Among various nanofillers, Nano Alumina (Al_2O_3) has gained importance due to its high hardness, excellent thermal stability, and chemical inertness (John & Nair, 2002). Several studies have reported that when Nano Alumina is properly dispersed in the polymer matrix, it significantly enhances load transfer efficiency, hardness (Raghul et al., 2021; Atmakuri et al., 2020).

IV. MATERIALS USED

Sisal

Sisal fiber is a natural lignocellulosic fiber obtained from the leaves of the Agave sisalana plant. It is one of the strongest natural fibers, known for its high tensile strength, good abrasion resistance, and biodegradability. The fiber is composed mainly of cellulose (65–72%), hemicellulose (10–14%), and lignin (8–12%) (Satyanarayana et al., 2007). Sisal fibers are lightweight and have a density of about 1.45 g/cm³, making them suitable for lightweight structural composites. However, the surface of untreated sisal fibers contains impurities such as waxes, oils, and lignin, which reduce adhesion with polymer matrices. To enhance bonding, the fibers are often alkali-treated (5% NaOH) to remove amorphous materials and improve surface roughness (Kabir et al., 2012). The treated sisal fibers provide improved interfacial adhesion, tensile strength, and hardness in polymer composites.

Key Properties:

- Tensile Strength: 500–700 MPa
- Density: 1.45 g/cm³
- Elongation at Break: 2–3%
- Moisture Absorption: 10–12%

Glass Fiber

S-glass fiber (Structural glass fiber) is a synthetic, high-strength glass fiber developed primarily for aerospace and defence applications. Compared to the commonly used E-glass fiber, S-glass exhibits higher tensile strength, elastic modulus, and temperature resistance (Callister & Rethwisch, 2020). It consists primarily of silica (SiO_2), magnesium oxide (MgO), and alumina (Al_2O_3). In composite materials, S-glass provides excellent load-bearing capacity, impact resistance, and dimensional stability. When combined with natural fibers like sisal, it forms hybrid composites that benefit from both sustainability (sisal) and high performance (S-glass).

Key Properties:

- Tensile Strength: 4,500–4,800 MPa
- Density: 2.46 g/cm³
- Elastic Modulus: 86–90 GPa
- Thermal Stability: up to 700°

Fig.1 Glass Fiber

Nano Alumina (Al_2O_3)

Nano Alumina (Al_2O_3) is a ceramic nanofiller with particle sizes typically ranging from 20 to 80 nm. It is widely used in polymer composites to enhance mechanical hardness, stiffness, and wear resistance (Hussain et al., 2006). Nano Alumina has a high surface area, excellent chemical inertness, and thermal stability, which enable it to act as a reinforcing agent that bridges the matrix and fiber interface. When properly dispersed, Nano Alumina particles improve load transfer between the fibers and matrix, leading to enhanced hardness and wear resistance (Ramesh, 2016). However, excessive filler content can cause particle agglomeration, leading to void formation and reduced strength. In this study, Nano Alumina was added in 1%, 1.5%, and 2% by weight of the total composite to determine its effect on hardness.

Key Properties:

- Particle Size: 20–80 nm
- Density: 3.95 g/cm³
- Hardness (Mohs): 9
- Melting Point: 2050°C
- Thermal Conductivity: ~30 W/m·K

Fig.2 Nano Alumina Powder

Epoxy Resin

Epoxy resin is a thermosetting polymer known for its excellent mechanical strength, chemical resistance, and adhesion to various reinforcements. The resin used in this study (typically LY556 or equivalent) is cured with a hardener (HY951), forming a rigid cross-linked structure. Epoxy serves as the matrix phase in the composite system, binding the fibers and fillers together while transferring loads between them. It also provides dimensional stability, moisture resistance, and uniform stress distribution within the composite (Mohanty et al., 2005). Epoxy resins are preferred for both structural and industrial applications, including aerospace, marine, and automotive components, due to their superior bonding capability with natural and synthetic fibers.

V. Methodology

Chemical treatment of sisal fiber

Raw sisal fibers were first cleaned in distilled water to remove surface dust and foreign particles, then air-dried for 24 hours. The cleaned fibers were immersed in a 5% (w/v) NaOH solution at room temperature (25–30°C) for 4 hours with occasional stirring to ensure uniform reaction. After treatment, the fibers were thoroughly washed with distilled water to remove residual NaOH and reaction by-products until the rinse water reached a neutral pH (≈7). The fibers were then air-dried for 24 hours, followed by oven drying at 60°C for 6 hours to remove moisture completely. The dried and treated sisal fibers were stored in airtight polyethylene bags to prevent moisture absorption prior to composite fabrication.

The Hand lay-up process

The hybrid composites were fabricated using the hand lay-up technique. Prior to fabrication, the sisal fibers were chemically treated with a 5% sodium hydroxide (NaOH) alkaline solution to remove surface impurities and enhance fiber–matrix interfacial adhesion. During the fabrication process, Nano Alumina (Al_2O_3) nanoparticles were incorporated into the epoxy matrix at varying weight fractions of 1%, 1.5%, and 2% of the total composite weight. The prepared mixtures of epoxy resin, hardener, treated sisal fibers, and S-glass fibers were uniformly layered within a mould of dimensions 300 mm × 300 mm × 3 mm. The lay-up was carefully compacted to remove air entrapment and ensure uniform fiber distribution. After curing at room temperature, the fabricated laminates were post-cured and subsequently machined to ASTM standard specimen dimensions for the Shore D hardness test (ASTM D2240). The final machining of samples was performed using water jet cutting to achieve high dimensional accuracy and defect-free edges.

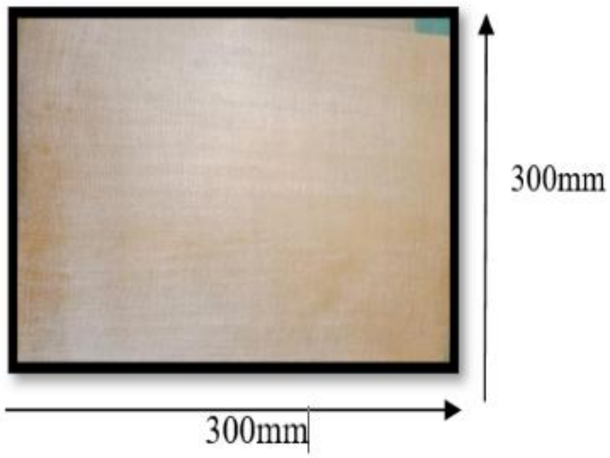

Fig.3 Developed slab of 300x300x3mm

Sample Preparations

Composite laminate of 300mm X 300mm X 3mm were fabricated according to ASTM standards (D2240) for Shore D Hardness tests.

Table 1 developed composite slab specifications

3 Different specimens	
SPECIMEN 1	*SISAL/S-GLASS/1% Nano Alumina (Al_2O_3)*
SPECIMEN 2	*SISAL/S-GLASS/1.5% Nano Alumina (Al_2O_3)*
SPECIMEN 3	*SISAL/S-GLASS/2% Nano Alumina (Al_2O_3)*

Hardnes Testing

The hardness of a material is its ability to resist surface indentation, scratching, or penetration under applied load. In polymer matrix composites, hardness is an important property that reflects surface strength, filler dispersion quality, and fiber–matrix adhesion. It also indicates the material's resistance to wear and deformation during service. The Shore D Hardness Test, as per ASTM D2240 standards, is specifically designed for harder plastics and composites. It is widely used to evaluate the hardness of fiber-reinforced polymer composites and assess the influence of nanofiller addition on surface performance.

Procedure:

1. The Shore D durometer was calibrated before testing.
2. The specimen was placed on a flat, rigid support to avoid deflection.
3. The indenter of the durometer was pressed vertically onto the surface of the specimen.
4. The reading was taken after 1 second of full contact between the indenter and the specimen surface.
5. For each sample, five readings were taken at different positions (at least 6 mm apart) to avoid interaction between indentations.
6. The mean Shore D hardness value was calculated and reported.

VI. RESULTS AND DISCUSSIONS

Table. 2 Results of Shore D hardness number

SPECIMENS	***SAMPLES***			***AVERAGE HARDENESS N0***
	Trail 1	***Trail 2***	***Trail 3***	
SPECIMEN 1	*64*	*63*	*65*	*64*
SPECIMEN 2	*65*	*68*	*70*	*67*
SPECIMEN 3	*71*	*73*	*74*	*72*

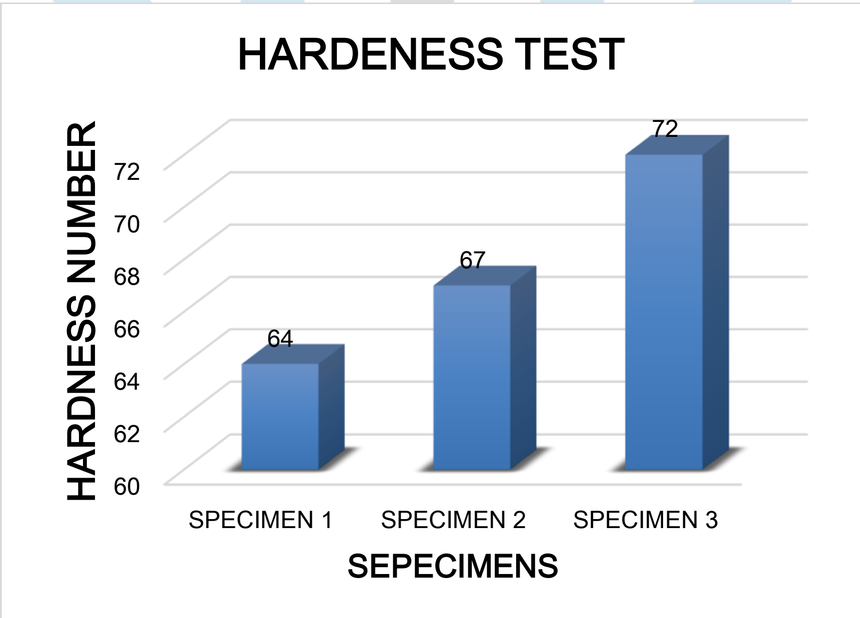

Fig. 4 Bar graph of Results of Shore D hardness number

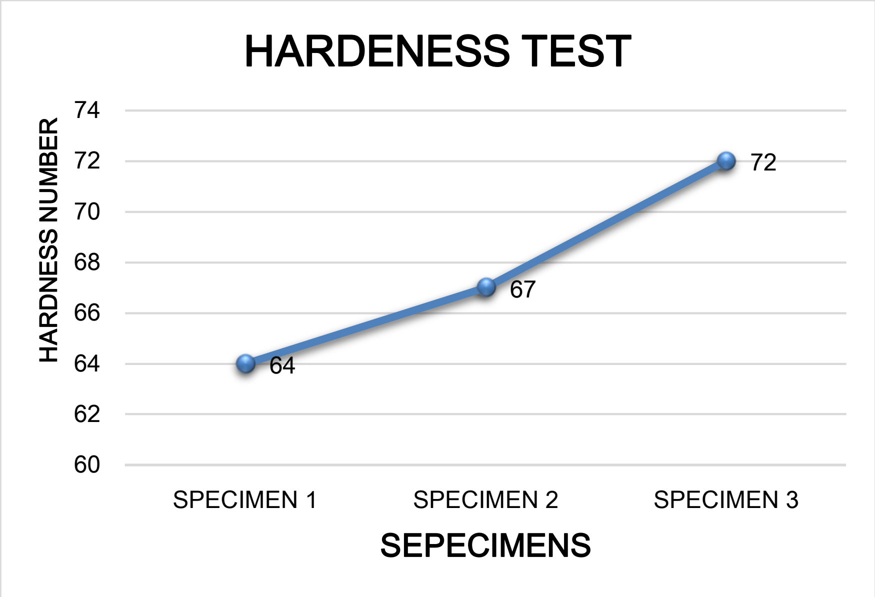

Fig. 5 Line graph of Results of Shore D hardness number

From above table and graph, it is observed that for the 1% Nano Alumina composite, the average Shore D hardness was recorded as 64, which serves as the baseline for comparison. In the case of the 1.5% Nano Alumina composite, the average hardness increased to 67, indicating a moderate improvement attributed to better nanoparticle dispersion and enhanced fiber–matrix interfacial bonding. The 2% Nano Alumina composite exhibited the highest hardness value of 72 Shore D, confirming that the addition of Nano-Al_2O_3 at this concentration significantly improves surface rigidity and load-bearing capacity of the hybrid composite. Overall, the experimental findings demonstrate that alkali treatment of sisal fibers combined with the incorporation of Nano-Alumina fillers leads to a notable enhancement in the mechanical properties, particularly hardness, of the developed composite materials.

VII. Conclusions

The hardness of the hybrid Sisal/S-Glass epoxy composites increased progressively with Nano-Alumina addition, proving that nano-filler reinforcement significantly strengthens the composite's surface integrity. These findings confirm the positive correlation between filler loading and hardness, highlighting the potential of Nano-Al_2O_3 as an effective reinforcement for improving the wear and mechanical resistance of natural–synthetic hybrid composites. The increasing value of the Hardness number is due to the addition of the nanofiller (Nano-Al_2O) and the resin helps in the binding the materials and constituents. The experimental study shows the chemical treatment and nano filler will improves the properties of the developed composite significantly.

VIII. Future scope

Future research may explore the reinforcements analyzed in this study in combination with different matrix materials to evaluate their compatibility and performance variations. Additionally, further experimental investigations involving tensile, flexural, and impact strength tests are recommended to achieve a comprehensive mechanical characterization of the developed hybrid composites. Such studies would offer a deeper understanding of their load-bearing capacity, deformation behavior, and failure mechanisms under various loading conditions.

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