engineering proceedings

Proceeding Paper

Experimental Investigation on the Impact of Tungsten Carbide Reinforcement on the Mechanical Properties of Sisal-Fiber-Reinforced Composites †

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† Presented at the International Conference on Processing and Performance of Materials, Chennai, India, 2–3 March 2023.

Abstract: Sisal-fiber-reinforced composites have garnered significant attention across various industries owing to their favorable attributes, including cost-effectiveness, biodegradability, and lightweight characteristics. Nevertheless, the need to enhance their mechanical and tribological properties has become imperative to meet the growing demand for high-performance materials. This study explores the impact of tungsten carbide (WC) particle reinforcement on the mechanical and tribological properties of sisal fiber composites. Composites were prepared by incorporating varying WC percentages (3%, 6%, and 9%) into the sisal-fiber–epoxy matrix. Flexural tests revealed a notable increase in flexural strength as WC content increased. Izod impact tests demonstrated superior impact resistance with higher WC content. Furthermore, pin-on-disc wear testing identified enhanced wear resistance in composites containing 9% WC reinforcement. These findings illustrate the potential of WC-reinforced composites for applications necessitating improved strength, impact resistance, and wear resistance, positioning them as promising materials for diverse industries.

Keywords: sisal fiber composite; tungsten carbide; nanoparticles; SEM

Citation: Thirupathy, M.; Vadivel, M.; Subbiah, T.; Pathinettampadian, G. Experimental Investigation on the Impact of Tungsten Carbide Reinforcement on the Mechanical Properties of Sisal-Fiber-Reinforced Composites. *Eng. Proc.* **2024**, *61*, 40. https://doi.org/10.3390/engproc2024061040

Academic Editors: K. Babu, Anirudh Venkatraman Krishnan, K. Jayakumar and M. Dhananchezian

Published: 6 February 2024

1. Introduction

Fiber-reinforced composites are well known for their unique combination of high strength, low weight, and excellent mechanical properties. They typically consist of reinforcing fibers embedded within a matrix material, providing structural integrity and load-bearing capabilities [1,2]. Natural fibers like sisal have gained attention in various industries, including automotive, construction, and aerospace, due to their renewable and sustainable nature. These fibers offer benefits such as cost-effectiveness, low density, and good thermal stability. Incorporating natural fibers like sisal into a suitable matrix material can significantly enhance their mechanical properties, including tensile strength and modulus [3,4].

Epoxy resin is a widely used matrix material for fiber-reinforced composites. It offers excellent adhesion to sisal fibers, promoting strong interfacial bonding and improved load transfer [5]. Epoxy composites are known for their high strength, stiffness, and resistance to environmental factors, making them ideal for structural applications. Furthermore, epoxy resins can be customized to meet specific requirements by adjusting curing conditions and incorporating additives [6]. In the pursuit of further improving the mechanical properties of sisal fiber composites, the addition of nanoparticles has gained significant attention.

Nanoparticles such as tungsten carbide (WC), titanium carbide (TiC), and silicon carbide (SiC) have been explored due to their exceptional mechanical and tribological properties. These nanoparticles offer advantages like high hardness, wear resistance, and thermal stability [7,8].

Tungsten carbide (WC) reinforcement has shown remarkable improvements in the mechanical behavior of fiber composites. The addition of WC nanoparticles has led to significant enhancements in flexural strength, stiffness, and impact resistance, thanks to the synergistic effects between the nanoparticles and the fiber–matrix interaction [9,10]. Achieving an effective dispersion and strong interfacial bonding between WC nanoparticles and the matrix is critical for optimizing the overall composite performance. Similarly, titanium carbide (TiC) and silicon carbide (SiC) nanoparticles have been examined as reinforcement materials for fiber composites. These nanoparticles exhibit excellent mechanical properties, including increased tensile and flexural strength, as well as a resistance to impact [11].

The efficient dispersion and uniform distribution of these nanoparticles within the matrix are essential for successful integration into fiber composites [12,13]. Various processing methods, such as high-energy ball milling, sonication, and melt mixing, have been employed to achieve uniform dispersion, promoting intimate mixing and enhancing mechanical performance. Beyond mechanical properties, wear resistance is crucial in many applications. The addition of WC, TiC, and SiC nanoparticles has improved wear resistance, reducing material loss and extending the service life of composites [14]. The hardness and wear resistance of these nanoparticles contribute to reduced friction and wear rates.

This research focuses on experimentally assessing the impact of tungsten carbide (WC) reinforcement on the mechanical properties of sisal-fiber-reinforced composites. This study aims to evaluate different percentages of WC additives on the composites' flexural strength, impact resistance, and wear resistance. This research involves preparing composite specimens with varying WC percentages using epoxy as the matrix material. Mechanical tests, including flexural and impact tests, are conducted to provide insights into how WC reinforcement enhances the mechanical properties of sisal fiber composites.

2. Material Preparation

2.1. Material Preparation

In our study, we conducted experimental research to explore the mechanical and tribological properties of alkaline-treated sisal fibers reinforced with 50-nanometer-sized tungsten carbide (WC) nanoparticles in an epoxy medium. Our goal was to achieve uniform WC particle dispersion within the composite. We preheated WC nanoparticles at 150 °C for an hour to enhance compatibility with the epoxy matrix, while simultaneously warming the epoxy resin to reduce its viscosity. We added three WC percentages (3%, 6%, and 9%) to the epoxy and stirred continuously for 30 min to ensure proper dispersion as shown in Table 1. The nanocomposite was then fabricated using the hand layup technique to evenly impregnate the epoxy-WC mixture onto alkaline-treated sisal fibers. After adding a hardener to expedite curing, the composite samples dried under atmospheric conditions for 24 h to attain the desired mechanical properties.

Table 1. Composition of prepared composites.

Composite Composition	Sisal Fiber (%)	Epoxy Resin (%)	WC Nanoparticles (%)
Composite 3% WC	40%	57%	3%
Composite 6% WC	40%	54%	6%
Composite 9% WC	40%	51%	9%

Table 1 summarizes the composite compositions, maintaining sisal fiber content at 40%. Epoxy resin content varied with WC nanoparticle percentages, 3% WC had 57% epoxy resin, 6% WC had 54%, and 9% WC had 51%, totaling 100% composition while increasing WC content from 3% to 9%. These composites underwent various tests, including tensile, flexural, hardness, and wear tests, assessing mechanical strength, stiffness, hardness, and wear resistance.

2.2. Flexural Test

In this research, we assessed the composite's flexural strength using the three-point flexural test method following the ASTM D790 standard. This test is a common method for evaluating a material's resistance to bending or deformation under a three-point loading configuration. Test specimens, measuring 120 mm in length, 15 mm in width, and 5 mm in thickness, were prepared. The span width, the distance between the supports where the specimen rests during the test, was set to 16 mm. Figure 1 illustrates the specimen used in the test and the experimental machine setup.

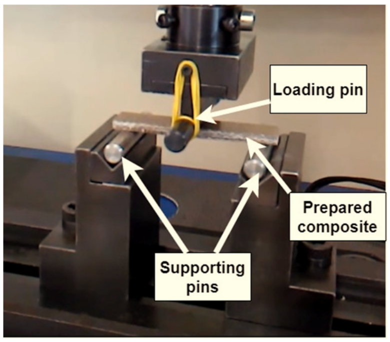

Figure 1. Flexural test.

The flexural test utilized the Instron 3382 machine, a standard choice for evaluating material mechanical properties. This machine applies a controlled load to the specimen's center, resulting in bending. The test ran at a consistent speed of 3.2 mm/min, and flexural strength (σ_f) was calculated using the following formula:

$$\sigma_f = (3FL)/(2bh^2) \quad (1)$$

where:

σ_f: flexural strength (MPa or psi);
F: maximum load applied (N or lb);
L: span length (mm or inches);
b: specimen width (mm or inches);
h: specimen thickness (mm or inches).

This formula, applied to data from the three-point flexural test, determined the composite material's flexural strength, revealing its resistance to bending. This research also included an impact test to assess the composite's ability to withstand sudden loading or impact. The Izod test, conducted following ASTM D256 standards, is a well-established method for evaluating material impact strength. An Izod testing machine, designed for impact tests, was used. It involves a pendulum-type impactor striking the specimen to create a sudden impact, and the energy absorbed during fracture is measured to determine the material's impact resistance. Composite specimens were prepared with specified dimensions as per standard requirements, and the Izod testing machine was setup with the appropriate pendulum weight and height for precise and consistent impact energy delivery. Figure 2 depicts the impact testing machine used in this research.

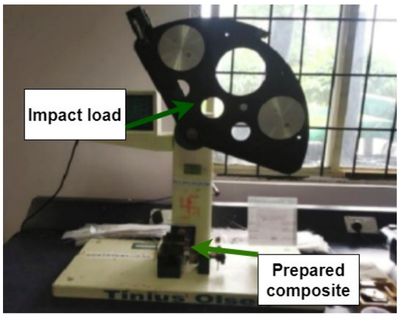

Figure 2. Impact test specimen.

The impact test involved releasing a pendulum to strike the notched specimen and recording energy absorbed during fracture, assessing its ability to withstand sudden loads. For the wear test, following ASTM G99 standards, we used a pin-on-disc wear apparatus to gauge the composite's wear resistance. Pins with specific dimensions, made from the composite, were tested against a rotating disc under a defined load. Figure 3 illustrates the setup. The test continued for a set duration or until a specific wear depth was reached, and the wear rate was calculated based on measurements during the test.

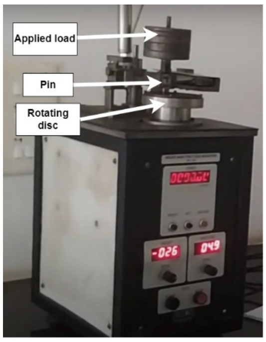

Figure 3. Wear test machine used in this research.

In our study, we analyzed specific wear rate, coefficient of friction, and friction force to evaluate wear behavior and friction characteristics of the composite material. Specific wear rate measures the material worn away per unit sliding distance or time, calculated by dividing volume loss (V) by the product of applied normal load (F) and sliding distance (d). Lower specific wear rates indicate better wear resistance. The coefficient of friction, a dimensionless value, represents the ratio of frictional force (Ff) to applied normal load (Fn), providing insights into material friction. A higher coefficient of friction implies more resistance to sliding. Friction force opposes relative motion between sliding surfaces, calculated by multiplying the coefficient of friction (μ) by applied normal load (Fn), quantifying the force required to initiate or maintain motion between surfaces.

3. Result and Discussion

3.1. Flexural Test

The flexural test results displayed a clear link between the percentage of tungsten carbide (WC) additives and the sisal fiber composite's flexural strength. The flexural strength, a key indicator of a material's resistance to bending, increased with higher WC content, as depicted in Table 1 and Figure 4. The composite with 3% WC achieved a flexural strength of 97 MPa, which significantly improved to 115.3 MPa at 6% WC, and further increased to 127.8 MPa at 9% WC. This enhancement is attributed to the reinforcing effect of WC, bolstering the material's ability to withstand bending forces and enhance its structural integrity. These findings highlight the beneficial impact of WC particles on the composite's mechanical properties. Table 2 provides a comprehensive summary of flexural strength values, and Figure 4 visually compares these compositions and their respective flexural strengths.

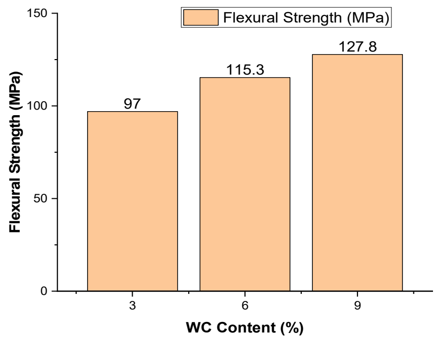

Figure 4. Flexural strength of the composite.

Table 2. Flexural strength of sisal fiber composite with WC additives.

WC Content (%)	Impact Strength (J/m)
3	520.34
6	544.3
9	573.44

3.2. Impact Test

In this research, we conducted an impact test following ASTM D256 standards to assess the impact strength of the composite. Impact strength measures a material's ability to withstand unexpected loading or impact forces without fracturing or breaking. The results revealed the impact of tungsten carbide (WC) additives on the composite's impact strength. Table 3 presents the impact test results, showing the impact strength values for various percentages of WC additives. The composite with 3% WC additives displayed an impact strength of 520.34 J/m, while the 6% WC composite showed improved strength at 544.3 J/m, and the 9% WC composite exhibited an even higher impact strength at 573.44 J/m. These findings highlight the positive influence of WC additives on the composite's impact strength.

Table 3. Impact test result.

WC Content (%)	Flexural Strength (MPa)
3	97
6	115.3
9	127.8

The impact test results, presented in Table 3 and Figure 5, provide valuable insights into how WC reinforcement affects the composite's impact performance. These findings are essential for optimizing composite materials in applications demanding strong impact resistance, like structural components under dynamic loads or protective gear. The results reveal a clear trend: the addition of WC particles enhances impact strength by improving the material's energy absorption and dissipation during impact loading. This translates to a higher resistance to fracture or failure under impact conditions. Figure 5 visually represents the impact strength data, offering a graphical comparison of impact strengths across different composite compositions with varying WC percentages.

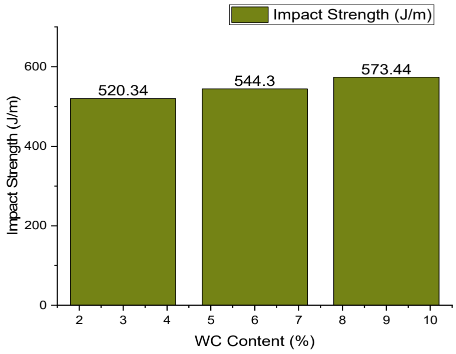

Figure 5. Impact test result.

Moving on to the wear test, we utilized a pin-on-disc wear apparatus (Figure 6) to evaluate the composite's wear performance under specific conditions. Table 4 outlines the results, including load, speed, and sliding distance. For a fixed load, speed, and sliding distance, the composite with 9% WC additives exhibited the lowest specific wear rate, friction coefficient, and sliding distance. Next, the composite with 6% WC additives displayed slightly higher values, while the composite with 3% WC additives showed the highest values among the tested compositions. These findings indicate that the addition of WC particles improves wear resistance, with the composite featuring 9% WC additives demonstrating the best wear performance. This improvement is attributed to the enhanced mechanical properties and abrasion resistance provided by WC reinforcement. Figure 6 visually complements the wear test results, showing superior wear resistance for the composite with 9% WC additives and higher wear rates with increasing WC content.

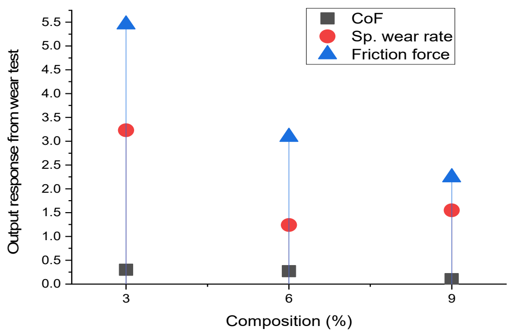

Figure 6. Responses from wear test.

Table 4. Result from the wear test.

Composition (%)	Load (N)	Speed (RPM)	Sliding Distance (m)	COF	Sp. Wear Rate mm^3/Nm	Friction Force (N)
3	20	100	27.72	0.3	3.23	5.45
6	20	100	27.72	0.27	1.24	3.09
9	20	100	27.72	0.1	1.55	2.24

3.3. SEM Analysis

In our research, SEM analysis was conducted to evaluate the nanoparticle dispersion within the tungsten carbide (WC) reinforcement. Figure 7 presents SEM images illustrating dispersion characteristics at various WC reinforcement percentages. Figure 7a shows the SEM image of the composite with 3% WC reinforcement, displaying scattered WC particles within the sisal-fiber-reinforced composites, with a somewhat uneven dispersion. Figure 7b illustrates the composite with 6% WC reinforcement, revealing an improved particle dispersion compared to the 3% composition. The particles are more evenly distributed, indicating progress in achieving a better dispersion. Figure 7c displays the SEM image of the composite with 9% WC reinforcement, demonstrating a uniform dispersion of WC particles within the sisal-fiber-reinforced composites. The particles are evenly distributed without noticeable agglomeration, representing a successful uniform dispersion at the 9% reinforcement level.

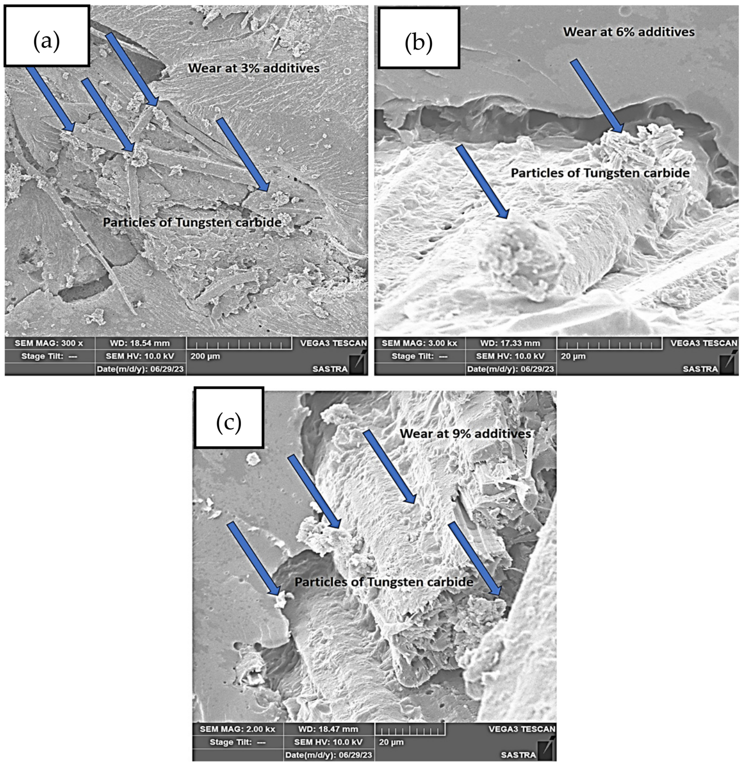

Figure 7. SEM analysis of the prepared composites of varying composition of WC (**a**) 3% WC reinforcement (**b**) 6% WC reinforcement (**c**) 9% WC reinforcement.

The SEM analysis highlights that achieving a uniform dispersion of WC particles, as observed in the 9% reinforcement composite, enhances wear resistance. The absence of agglomeration further supports improved wear resistance. This uniform dispersion is crucial for optimizing both mechanical and tribological properties by ensuring an effective load transfer and strengthening the composite matrix.

4. Conclusions

In summary, this research aimed to assess the impact of tungsten carbide (WC) reinforcement on sisal-fiber-reinforced composites' mechanical and tribological characteristics. Composites with varying WC proportions were fabricated and extensively tested. Flexural testing revealed a direct relationship between WC content and increased flexural strength, ranging from 97 MPa (3% WC) to 127.8 MPa (9% WC), emphasizing WC's strengthening effect. Impact testing demonstrated a significant rise in impact strength, reaching 573.44 J/m (9% WC), enhancing the composite's resistance to fractures. Wear testing revealed that the 9% WC composite displayed the lowest specific wear rate, friction coefficient, and sliding distance, underscoring WC's role in improving wear resistance. SEM analysis confirmed the importance of a uniform WC particle dispersion in enhancing mechanical and tribological properties, particularly observed in the 9% WC composite without agglomeration. These findings highlight WC's effectiveness in enhancing sisal-fiber-reinforced composites' overall performance.

Author Contributions: M.T. and M.V. were involved in data collection, data analysis, manuscript writing. T.S. and G.P. were involved in conceptualization, data validation, and critical review of manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data are available in the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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