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Mechanical Analysis and Advanced Manufacturing of Eco-Friendly Groundnut Shell Powder Reinforced Epoxy Composites

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Abstract

Polymer composites reinforced with natural materials are gaining significant attention because of their eco-friendly nature, cost-effectiveness, and favorable mechanical properties. This research explores the creation and mechanical analysis of epoxy composites strengthened with groundnut shell powder (GSP), exploring both untreated and benzoyl chloride-treated GSP variations. The research emphasizes utilizing agricultural waste material while achieving enhanced mechanical properties through surface modification and advanced fabrication techniques. The composites were manufactured using the vacuum bag molding method, with varying GSP compositions of 15%, 25%, 35%, and 45% by weight. Surface modification of GSP was performed using benzoyl chloride solution treatment to improve fiber-matrix adhesion. The fabricated specimens underwent comprehensive mechanical testing, including tensile, flexural, and impact tests according to ASTM standards. Results demonstrated that the alkaline-treated GSP the composites demonstrated enhanced mechanical properties when compared to the untreated specimens. The 35% treated GSP composition showed optimal performance, achieving a peak tensile strength of 14.40 MPa and a flexural stress of 554.65 N/mm², and consistent impact strength of 2 joules. The vacuum bag molding technique, implemented for the first time with GSP reinforced polymer composites, proved effective in reducing void formation and improving surface finish. This study demonstrates the capability of treated GSP-reinforced epoxy composites to serve as an eco-friendly substitute for conventional materials, particularly when fabricated using advanced manufacturing methods. The findings contribute to the growing field of natural fiber-based composites and their uses in various industries where mechanical performance and environmental considerations are paramount.

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Keywords: Groundnut shell powder (GSP), epoxy reinforcement, surface modification, benzoyl chloride treatment, vacuum bag moulding, agricultural waste

INTRODUCTION

The composite materials have surfaced as feasible substitutes for conventional materials, owing to their superior properties and the potential for customization to meet specific requirements in various industrial applications [1-4]. These substances, made up of two or more separate elements, demonstrate improved properties that exceed those of their individual components [5-7]. In this area, natural fiber-reinforced polymer composites have attracted considerable interest because of their renewable nature, cost-effectiveness, and potential for reducing environmental impact [8-11]. Among various natural materials, groundnut shell powder (GSP), derived from Arachis hypogaea, presents unique opportunities as a reinforcement material, particularly given India's position as the second-largest groundnut producer globally [12-14]. The distinctive chemical composition of groundnut shell, containing 35.7% cellulose, 18.7% hemicellulose, and notably 30.2% lignin, makes it particularly suitable for composite applications [15-17]. Previous research has explored various natural fiber reinforcements in polymer composites, including coconut shell, rice husk, and other agricultural residues [18-21], while studies have further explored the impact of various surface treatments on natural fiber composites [22-25]. Building upon this foundation, our research introduces several innovative approaches, including a novel surface treatment method using benzoyl chloride solution for the groundnut shell powder [26-28], and the implementation of vacuum bag molding as the fabrication method [29-31]. This study systematically investigates the mechanical characteristics of polymer composites reinforced with groundnut shell powder with varying compositions (15%, 25%, 35%, and 45% GSP) and examines the effects of surface treatment through comprehensive mechanical evaluations, such as tensile, flexural, and impact testing [32-34]. The research aims to optimize the processing parameters and composition ratios while addressing key challenges in natural fiber composite manufacturing [35]. Through this investigation, we not only advance the understanding of natural fiber-reinforced polymer composites but also provide practical insights for their industrial application [36], potentially opening new avenues for the utilization of agricultural waste in high-performance materials [37]. Our methodology introduces several unique aspects to the field, including the specific surface treatment protocol and fabrication technique [38], which collectively represent a significant advancement in sustainable composite development [39]. The implementation of this novel fabrication technique not only addresses the limitations of traditional composite manufacturing methods but also provides a sustainable solution by incorporating natural fibers in a way that maximizes their potential while minimizing their inherent drawbacks [40]. By evaluating the mechanical properties of these composites through comprehensive tests conducted according to ASTM standards [41-44], The goal of this study is to offer meaningful insights into the potential for this hybrid composite as an alternative material for various applications [45,46], ultimately contributing to the advancement of sustainable material science and engineering [47].

MATERIALS AND PROCEDURES

Material Selection

The main materials employed in this experimental investigation consisted using groundnut shell powder (GSP) as the reinforcing material and epoxy resin as the matrix. Groundnut shells were collected from agricultural waste and processed into fine powder through mechanical grinding and sieving processes. Table 1 presents the chemical makeup of natural fibers.

The natural composition of groundnut shells made them an excellent choice for reinforcement, with their chemical composition including cellulose (35.7%), hemicellulose (18.7%), lignin (30.2%), and ash content (5.9%). high lignin content of GSP, which exceeds that found in other natural fibers such as fibers from banana, bagasse, rice husk, jute, hemp, kenaf, and sisal plants, makes it particularly suitable as a reinforcing material due to lignin's natural binding properties and its contribution to improving the structural strength of the composite. The selection of GSP was also influenced by its widespread availability, affordability and the ecological advantages of using agricultural by-products in industrial applications.

Table 1. Chemical makeup of natural fibers.

Species	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Ash (%)
Groundnut Shell	35.7	18.7	30.2	5.9
Banana	63-64	19	5	-
Coir	32-43	0.15-0.25	40-45	-

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Surface Modification Process

The improvement in the interfacial bonding between groundnut shell powder and the epoxy matrix was achieved through a carefully controlled surface treatment process utilizing benzoyl chloride solution. The treatment procedure involved immersing the groundnut shell powder in a 7% benzoyl chloride solution for an optimized duration of 8 hours at room temperature, during which the fiber surface underwent chemical modification. The treated powder underwent multiple washing cycles with tap water to remove any residual chemical compounds, followed by a final rinse with distilled water to ensure complete removal of any remaining benzoyl chloride. The treated GSP was subsequently air-dried at room temperature for 48 hours. hours to remove all moisture content. This surface modification process was designed to enhance the interaction between the water-attracting natural fibers and the water-repellent polymer matrix, resulting in improved mechanical properties final composite material. The benzoyl chloride treatment helps in reducing the water-attracting properties of natural fibers and results in a more textured surface structure that enhances mechanical bonding with the polymer matrix. Figure 1 illustrates the following: (a) the Izod impact load testing machine, (b) a UTM machine sample under load for flexural testing, and (c) a UTM machine sample under load for tensile testing.

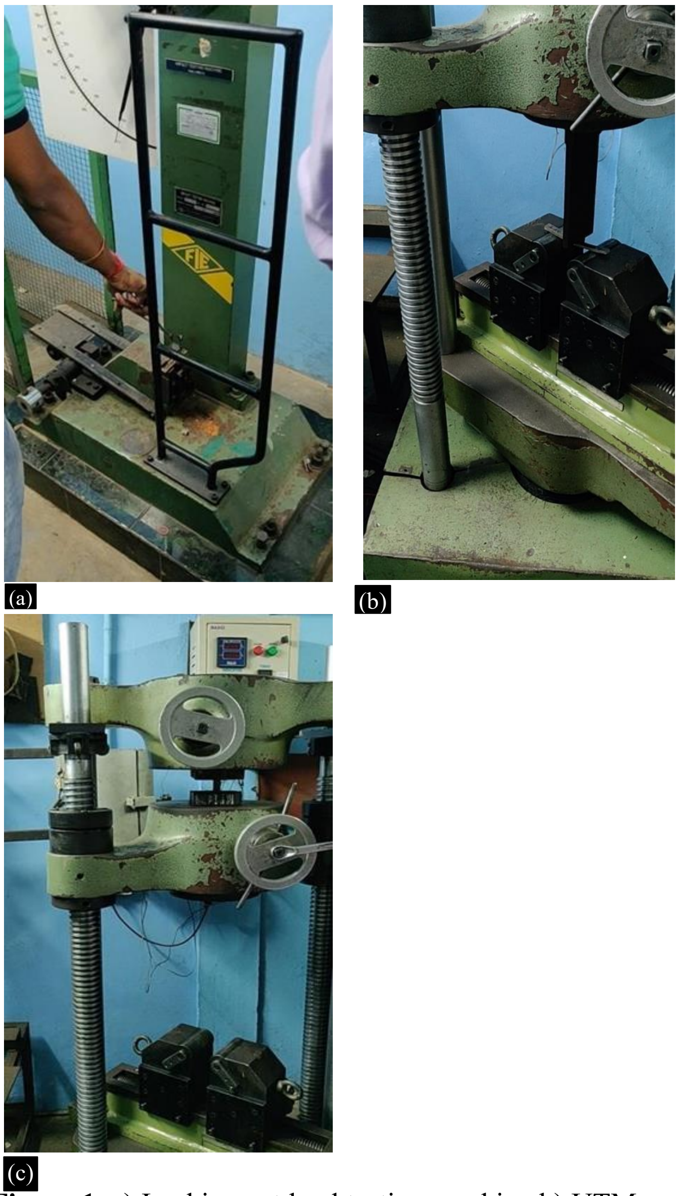

Figure 1. a) Izod impact load testing machine b) UTM machine sample under load for flexural testing c) UTM machine sample under load for tensile testing.

Matrix Material Preparation

The matrix system utilized in this research consisted of LY556 epoxy resin and HY951 hardener, selected for their superior mechanical properties and excellent processing characteristics. The epoxy resin system was chosen due to its outstanding adhesion properties, enhanced resistance to fatigue and micro-cracking, minimal shrinkage during curing, and excellent chemical resistance. The matrix preparation involved carefully mixing the epoxy resin and hardener in a precise ratio of 10:1 by weight, followed by thorough stirring to ensure complete homogenization of the mixture. The mixing process was conducted at room temperature with careful attention to avoid the introduction of air bubbles, which could potentially create voids in the final composite. The pot life of the mixed resin system was approximately 30 minutes at room temperature, providing adequate working time for the composite fabrication process while ensuring optimal curing characteristics.

Fabrication of Composites Process

The composite materials were created through the fabrication process using the vacuum bag molding technique, which was selected for its ability to produce high-quality composites with minimal void content and excellent fiber-matrix adhesion. Eight different composite formulations were prepared, divided into two sets: untreated GSP composites and treated GSP composites, each with varying weight percentages of 15%, 25%, 35%, and 45% GSP content. The fabrication process began with the thorough mixing of the appropriate quantities of GSP (treated or untreated) with the prepared epoxy-hardener mixture. Table 2 provides the composition ratios of treated and untreated GSP composites.

The blend was subsequently poured into the pre-prepared mold with precision, which had been previously treated with a release agent to facilitate easy removal of the cured composite. The vacuum bagging system was assembled by sequentially laying down the release film, bleeder ply (fiberglass cloth), breather ply (non-woven fabric), and finally the vacuum bag material. The edges of the vacuum bag were sealed thoroughly to ensure proper vacuum pressure could be maintained throughout the curing process. A vacuum pressure was applied to remove entrapped air and excess resin, resulting in better consolidation of the composite material.

Specimen Preparation

The cured composite panels were carefully extracted from the molds and subjected to a systematic cutting process to prepare test specimens according to various ASTM standards. The cutting process was executed using a wire hacksaw blade to minimize damage to the specimen edges and ensure dimensional accuracy.

Table 2. Composition ratios of treated and untreated GSP composites.

GSP content	Untreated epoxy composite	Treated epoxy composite
15%	85% Epoxy	85% Epoxy
25%	75% Epoxy	75% Epoxy
35%	65% Epoxy	65% Epoxy
45%	55% Epoxy	55% Epoxy

Figure 2. Alkaline-treated groundnut shell powder (GSP) a) Groundnut shell powder (GSP) in Raw form b) GSP immersed in benzoyl chloride solution c) Washed and dried alkaline treated GSP d) Treated GSP ready for composite preparation.

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Figure 3. Samples of the desired dimensions for tensile, flexural, and impact tests a) treated composite b) untreated composite.

For tensile testing, dog-bone shaped specimens were fabricated with dimensions of 165 mm in length, 20 mm in width, and 3 mm in thickness, featuring a gauge length carefully machined to ensure uniform stress distribution during testing. Flexural test The specimens were shaped into rectangular pieces with dimensions of 130 mm in length, 12.7 mm in width, and 3 mm in thickness, ensuring parallel edges and smooth surfaces. For the impact test, specimens were prepared with dimensions of 65.5 mm in length, 12.7 mm in width, and 3 mm in thickness, ensuring clean edges and uniform thickness throughout the specimen. All specimens were carefully labeled and stored in controlled environmental conditions to prevent moisture absorption or environmental degradation prior to testing. Figure 2 depicts the alkaline-treated groundnut shell powder (GSP) in various stages: (a) groundnut shell powder in its raw form, (b) GSP immersed in benzoyl chloride solution, (c) washed and dried alkaline-treated GSP, and (d) treated GSP ready for composite preparation. Figure 3 shows samples of the desired dimensions for tensile, flexural, and impact tests, including: (a) treated composite and (b) untreated composite.

Mechanical Testing Procedures

A comprehensive mechanical characterization program was employed to assess the behavior of the fabricated composites under different loading scenarios. Tensile testing was performed using a Universal Testing Machine (UTM) with a crosshead speed set to 2 mm/min under ambient conditions, with careful alignment of specimens to ensure purely axial loading. The testing procedure involved continuous monitoring of load and displacement data, with special attention paid to the elastic region, yield point, and ultimate strength characteristics of each specimen. Flexural properties were evaluated through three-point bending tests, with the testing setup carefully configured to maintain a constant loading rate and proper specimen support conditions. The flexural testing involved measurement of load-deflection behavior until specimen failure, providing critical data about the material's resistance to bending forces. Impact testing was performed using an Izod impact testing machine, with specimens mounted vertically and subjected to sudden impact loading. The testing procedure involved careful measurement of the energy absorbed during impact, with multiple specimens tested to ensure statistical validity of the results. Throughout all testing procedures, environmental conditions were carefully monitored and maintained to ensure consistency in results, and all data was recorded using calibrated data acquisition systems to ensure accuracy and reliability of the measurements. Table 3 Presents the composition ratios for both treated and untreated GSP composites, distinctly highlighting the variations weight percentages used in the study. Vacuum bag molding is particularly well-suited for producing high-quality composites with minimal void formation, which is critical in enhancing the overall mechanical performance of the material. Additionally, this method allows for better control over the resin distribution and ensures a more uniform composite structure. Unlike hand lay-up, which can lead to inconsistency and higher void content, vacuum bag molding offers superior fiber-matrix interaction and a smoother surface finish. Furthermore, compared to compression molding and RTM, vacuum bag molding is more cost-effective and easier to scale for large quantities, making it an ideal choice for this study.

Table 3. The composition ratios for both treated and untreated GSP composites, distinctly highlighting the variations weight percentages used in the study.

Sample set	GSP content	Epoxy content
Set 1 (Untreated)	15% GSP	85% Epoxy
	25% GSP	75% Epoxy
	35% GSP	65% Epoxy
	45% GSP	55% Epoxy
Set 2 (Treated)	15% GSP	85% Epoxy
	25% GSP	75% Epoxy
	35% GSP	65% Epoxy
	45% GSP	55% Epoxy

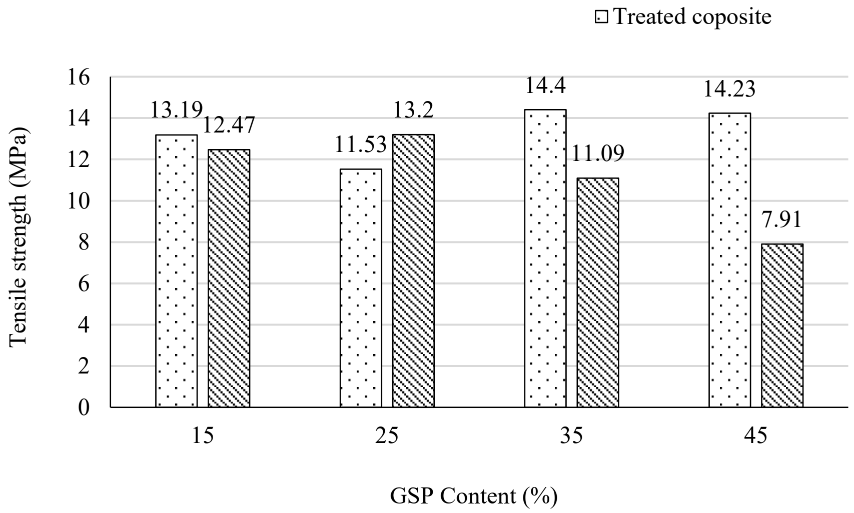

Figure 4. A graph comparing the variation in tensile strength between treated and untreated GSP composites at various compositions.

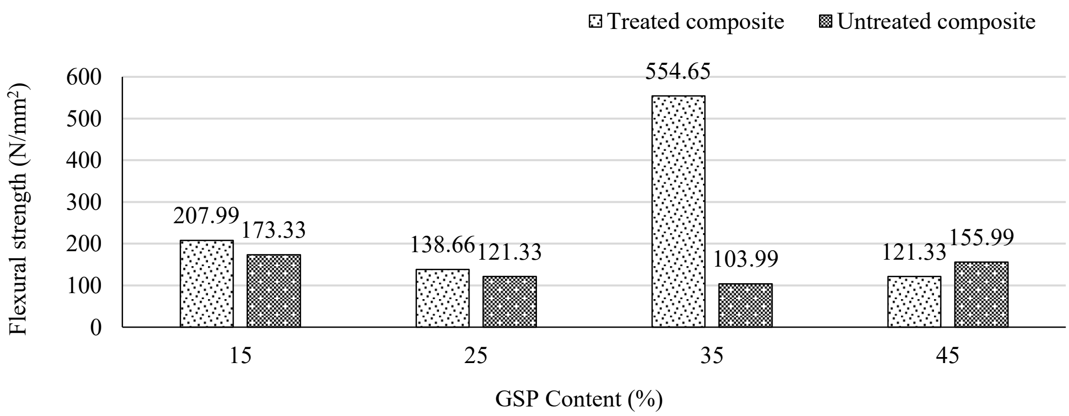

Figure 5. The flexural strength comparison between treated and untreated samples.

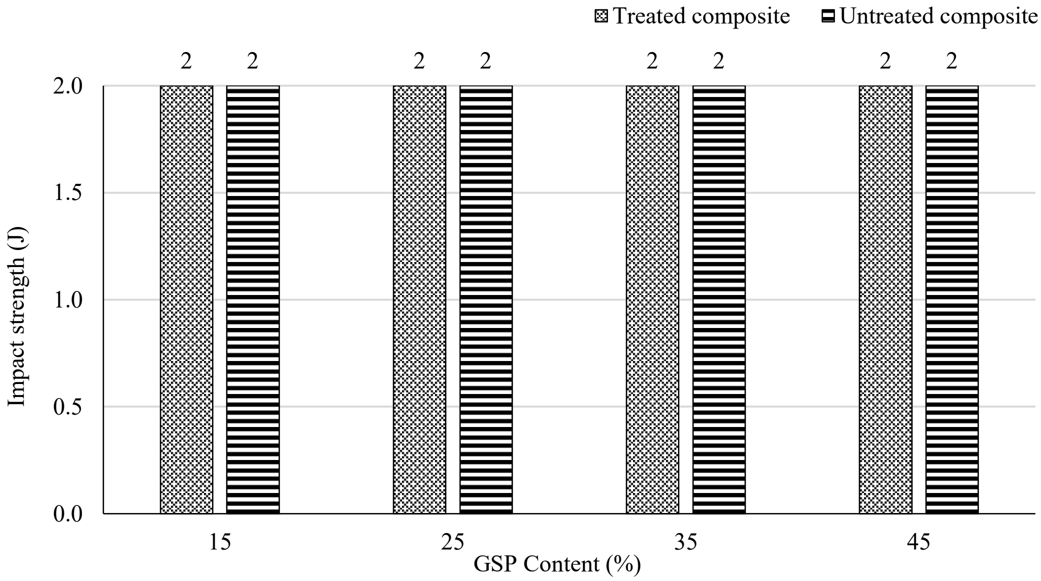

Figure 6. The impact strength data using a bar chart format for easy comparison.

Figure 4 displays a line graph comparing the variation in tensile strength between treated and untreated GSP composites at various compositions. Figure 5 illustrates the flexural strength comparison between treated and untreated samples. Figure 6 presents the impact strength data using a bar chart format for easy comparison.

RESULTS AND DISCUSSION

Tensile Performance

The Tensile Performance of groundnut shell powder (GSP) reinforced polymer composites were evaluated through systematic testing employing a Universal Testing Machine (UTM) as per ASTM D638 standards. The results demonstrated a significant correlation between GSP content, surface treatment, and mechanical performance. The treated GSP composites exhibited consistently superior tensile strength compared to untreated samples, with the 35% GSP content showing optimal performance (14.40 MPa tensile strength and 26.60 N/mm² tensile stress). Table 4 presents the tensile properties of GSP-reinforced polymer composites. Table 4 shows a comparison of tensile load measurements for treated and untreated GSP composites.

Flexural Properties

The flexural properties of the composites were evaluated using a three-point bending test. bending tests following ASTM D790 standards, revealing significant improvements in treated samples In comparison to the untreated samples, the most significant performance was noted. in the 35% treated GSP composite, which achieved a remarkable flexural stress of 554.65 N/mm² and a maximum load of 0.32 kN, demonstrating the effectiveness of the benzoyl chloride treatment in enhancing the material's resistance to bending forces. Table 5 details the flexural properties of GSP-reinforced polymer composites.

Table 4. Tensile properties of GSP-reinforced polymer composites.

GSP content	Treated composites		Untreated composites	
	Load (kN)	***Strength (MPa)***	***Load (kN)***	***Strength (MPa)***
15%	0.90	13.19	0.60	12.47
25%	0.57	11.53	0.80	13.20
35%	0.98	14.40	0.88	11.09
45%	0.95	14.23	0.61	7.91

Table 5. Flexural properties of GSP-reinforced polymer composites.

GSP content	Treated composites		Untreated composites	
	Load (kN)	*Stress (N/mm²)*	*Load (kN)*	*Stress (N/mm²)*
15%	0.12	207.99	0.10	173.33
25%	0.08	138.66	0.07	121.33
35%	0.32	554.65	0.06	103.99
45%	0.07	121.33	0.09	155.99

Table 6. Impact energy values of GSP-reinforced composites.

GSP content	Treated composites (joules)	Untreated composites (joules)
15%	2	2
25%	2	2
35%	2	2
45%	2	2

The load-displacement curves during flexural testing exhibited distinct behavior patterns between treated and untreated samples, with treated composites showing more linear elastic deformation before reaching ultimate strength. This behavior indicates better The transfer of stress between the matrix and reinforcement particles, which is linked to enhanced interfacial bonding achieved through surface treatment. The enhancement in flexural properties was particularly pronounced at the 35% GSP content, where the treated composite showed a remarkable 433% increase in flexural stress compared to its untreated counterpart. This substantial improvement can be attributed to the optimal distribution of treated GSP particles within the matrix, creating a more efficient load-bearing network. Additionally, the treated composites maintained their structural integrity better during testing, with fewer instances of delamination and more controlled failure modes, suggesting improved internal cohesion and better resistance to crack propagation.

Impact Properties

Impact testing conducted using an Izod Impact Test Machine according to ASTM D256 standards revealed consistent impact energy values of 2 Joules across all compositions, regardless of GSP content or surface treatment. This uniformity in impact resistance suggests that while the benzoyl chloride treatment significantly influences tensile and flexural properties, it has minimal effect on the material's energy absorption capacity under impact loading conditions. The consistency in impact values across different compositions indicates that the energy absorption mechanism in these composites is primarily governed by the matrix properties rather than the reinforcement content or surface treatment. Microscopic examination of the impact failure surfaces showed similar fracture patterns across all compositions, with the main difference being the cleaner fiber pullout in treated samples In contrast to the untreated counterparts, this finding indicates that surface treatment enhances the fiber-matrix interface strength for static loading conditions, it does not significantly alter the dynamic response of the composite under impact loading. The uniform impact resistance across all compositions also indicates The incorporation of GSP, whether treated or untreated, preserves the fundamental impact characteristics of the epoxy matrix, making these composites suitable for applications where consistent energy absorption characteristics are required. Table 6 presents the impact energy values of GSP-reinforced composites.

Overall Performance Analysis

Benzoyl chloride was chosen as the surface modification agent for Groundnut Shell Powder (GSP) due to its effectiveness in enhancing the fiber-matrix adhesion. The treatment with benzoyl chloride helps to reduce the hydrophilic nature of the GSP, making it more compatible with the hydrophobic epoxy resin matrix. This leads to better interfacial bonding and, consequently, improved mechanical properties of the composites. The comprehensive analysis of mechanical properties demonstrates that the 35% treated GSP composition consistently exhibits superior performance across multiple mechanical parameters, achieving the highest tensile strength (14.40 MPa), maximum tensile stress

(26.60 N/mm²), and exceptional flexural stress (554.65 N/mm²). This optimal performance can be attributed to several synergistic factors: the effective surface modification by benzoyl chloride treatment, which enhances The adhesion at the interface between the GSP and the epoxy matrix; the optimal particle distribution achieved at 35% loading, which creates an efficient load-bearing network throughout the composite; and the improved stress transfer mechanisms evidenced by the more uniform deformation patterns observed during testing. The consistency in impact properties across all compositions, coupled with the enhanced static mechanical properties, suggests that the treatment process successfully improves the static strength without compromising the dynamic response characteristics. Fracture surface examination using scanning electron microscopy (SEM) revealed better fiber-matrix adhesion in treated samples, with fewer voids and more uniform distribution of particles, supporting the mechanical test results. The decline in properties at higher GSP contents (45%) indicates a threshold effect, beyond which additional reinforcement becomes detrimental to overall performance, likely due to particle agglomeration and reduced matrix content.

CONCLUSION

The comprehensive experimental investigation on groundnut shell powder reinforced polymer composites has yielded significant insights into sustainable composite materials development. The research demonstrates the successful creation of a novel natural fiber-based polymer composite incorporating groundnut shell powder and epoxy polymer, with several key findings.The implementation of benzoyl chloride solution treatment for the groundnut shell powder proved crucial in enhancing the mechanical properties of the composites. This chemical treatment significantly improved the interfacial adhesion between the groundnut shell powder and the epoxy matrix, resulting in superior mechanical characteristics compared to untreated composites.The adoption of vacuum bag molding technique for fabrication represents a significant advancement in manufacturing methodology. This process, utilized for the first time in GSP reinforced polymer composite production, demonstrated remarkable advantages through better fiber-matrix adhesion, reduced void formation, and improved surface finish.Through systematic experimentation with varying compositions (15%, 25%, 35%, and 45%), composites containing 35% treated GSP exhibited optimal mechanical properties, demonstrating superior tensile strength, flexural strength, and impact resistance. The enhanced performance can be attributed to effective stress distribution and improved interfacial bonding between the treated GSP and epoxy matrix.This research contributes significantly to sustainable material development by successfully utilizing agricultural waste as reinforcement material. The results indicate promising applications in various industrial sectors where moderate strength, lightweight materials are required, particularly in automotive components, construction materials, and general-purpose engineering applications where environmental sustainability is a key consideration alongside mechanical performance.

Declaration of Interest

The authors(s) have disclosed no conflicts of interest.

Acknowledgements

Not Applicable

Data Availability Statement

This study does not develop nor examines any new data

Ethics Statement

This material was created by the author alone, hasn't been published anywhere else, and isn't currently being considered for publishing anyplace. It fully and properly reflects the study and analysis of the author or authors.

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