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Water Absorption and Mechanical Behaviour of Bagasse Fibre and Particle-Reinforced Hybrid Composite Materials

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Abstract

This study investigates the mechanical behaviour and water absorption characteristics of bagasse fibre and groundnut shell particle (GSP)-reinforced hybrid composites using a phenol-formaldehyde (PF) resin matrix. Varying weight fractions of GSP (5%, 10%, 15%, and 20%) were incorporated into the composites, with bagasse fibre content kept constant at 30% by weight. Tensile, flexural, and impact strengths were measured, and the water absorption behaviour was evaluated following ASTM standards.The results indicated a decrease in tensile strength as GSP content increased, with the highest value of 45 MPa observed at 5% GSP, and the lowest value of 32 MPa at 20% GSP. In contrast, flexural strength improved with increasing GSP content, reaching 70 MPa at 20% GSP compared to 55 MPa at 5% GSP. Similarly, the impact strength increased from 8 J/m at 5% GSP to 12 J/m at 20% GSP, attributed to the crack-arresting ability of GSP. Water absorption tests revealed that composites with higher GSP content absorbed more water, with the 20% GSP composite showing a water absorption rate of 6.8% compared to 2.5% for the 5% GSP composite after 72 hours. Moisture exposure led to significant reductions in mechanical properties, particularly in tensile and flexural strengths, where reductions of up to 20% and 20%, respectively, were observed at 20% GSP. Impact strength, however, showed a lesser reduction of around 10%. The study concluded that a 10% GSP content provided an optimal balance of mechanical performance and water resistance, making it suitable for applications such as automotive components and construction materials.

Keywords: Mechanical behaviour, water absorption, bagasse fibre, impact strength, hybrid composites

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INTRODUCTION

The increasing awareness of environmental sustainability and the urgent need to reduce the carbon footprint of industrial processes have driven significant interest in the use of natural fibres and agricultural waste as reinforcements in composite materials. Traditionally, synthetic fibres like glass and carbon fibres have been used in polymer composites due to their excellent mechanical properties. However, these materials are derived from non-renewable resources, are energy-intensive to produce, and present significant environmental challenges at the end of their lifecycle, including difficult recyclability and non-biodegradability. In contrast, natural fibres, such as bagasse, jute, coir, and flax, offer a renewable, biodegradable, and low-cost alternative for reinforcing polymer matrices.

Among these natural fibres, bagasse, the fibrous by-product of sugarcane processing, presents a particularly attractive option due to its abundance and low cost. Bagasse is typically disposed of as waste or used as fuel in sugarcane processing plants, but its potential as a reinforcement material for composites is now gaining attention. Chemically, bagasse is composed primarily of cellulose (45–55%), hemicelluloses (20–25%), and lignin (18–24%), which give it a high strength-to-weight ratio, good stiffness, and a structure conducive to reinforcing polymers. Its relatively high cellulose content, in particular, is responsible for its mechanical properties, as cellulose fibres provide rigidity and strength to the composite material [1-5].

In addition to bagasse, groundnut shell particles (GSP)—another agricultural waste product—have been explored as a reinforcement material. Groundnut (peanut) production generates large quantities of shell waste, which typically account for 25-35% of the total mass of the pod. Groundnut shells consist of cellulose (35.7%), hemicelluloses (18.7%), and lignin (18.7%), similar to other plant-based reinforcements. They are readily available and can be processed into fine particles that serve as fillers in polymer matrices. GSPs have been shown to enhance the mechanical properties of polymer composites by acting as rigid inclusions that resist deformation under mechanical stress [6-11]. Furthermore, they improve the biodegradability of the composite and reduce the overall cost of the material.

The phenol-formaldehyde (PF) resin used as the matrix material in this study is a widely used thermosetting polymer known for its excellent mechanical strength, thermal stability, and chemical resistance. PF resins are commonly used in the production of wood products, laminates, and insulation materials and they have been extensively studied in combination with natural fibres. However, the challenge remains in ensuring effective bonding between natural fibres and the hydrophobic PF matrix, as the hydrophilic nature of fibres like bagasse and groundnut shell particles can lead to poor interfacial adhesion and water uptake, which negatively affects mechanical properties and long-term durability [12-16].

The Role of Natural Fibres in Composite Materials

Natural fibre-reinforced polymer composites have several advantages over conventional composites. They offer:

- Low density, leading to lighter composite materials.
- Biodegradability, making them more environmentally friendly than composites reinforced with synthetic fibres.
- Low cost, as natural fibres are abundantly available as agricultural by-products.
- Non-toxicity and renewability, reducing the environmental and health risks associated with synthetic materials.

Despite these advantages, there are several challenges associated with the use of natural fibres. One significant drawback is their moisture absorption behaviour, which can lead to swelling, loss of dimensional stability, and degradation of mechanical properties when exposed to humid environments. Natural fibres are inherently hydrophilic due to the presence of hydroxyl groups in cellulose, hemicelluloses, and lignin, which can form hydrogen bonds with water molecules. This moisture sensitivity limits the use of natural fibre composites in certain applications, especially those involving exposure to water or high humidity. Additionally, natural fibres tend to have lower mechanical properties than synthetic fibres, which necessitate careful optimisation of fibre content, treatment processes, and matrix selection to achieve desirable properties in composite applications.

Hybrid Composites with Natural Fibres and Particles

Hybrid composites that combine different types of reinforcements, such as fibres and particles, offer a way to overcome some of the limitations of single-fibre composites. By hybridizing bagasse fibres with groundnut shell particles, it is possible to enhance the overall performance of the composite by leveraging the strengths of both materials. Bagasse fibres provide high tensile strength and stiffness, while groundnut shell particles contribute to the rigidity of the matrix and reduce the cost and density of the composite. Furthermore, the combination of fibres and particles can lead to improved mechanical properties, such as tensile strength, flexural strength, and impact resistance, by promoting better stress transfer within the composite.

Previous studies on hybrid composites have demonstrated that the inclusion of natural particles, such as groundnut shell or rice husk, in fibre-reinforced polymers can lead to notable improvements in properties. The particles can fill voids in the matrix, improve fibre-matrix adhesion, and act as crack arresters during mechanical loading, thereby improving the composite's toughness and reducing its tendency to fracture under impact. In this study, groundnut shell particles are chosen as the secondary reinforcement to enhance the mechanical integrity of the bagasse fibre composites [17-21].

Scope of the Study

This research aims to develop and characterise bagasse fibre and groundnut shell particle-reinforced hybrid composites using a phenol-formaldehyde matrix. The primary objectives of the study are:

1. To investigate the mechanical properties (tensile, flexural, and impact strength) of the hybrid composites as a function of groundnut shell particle content.
2. To evaluate the water absorption and thickness swelling behaviour of the composites under prolonged water exposure, assessing their suitability for applications in moisture-sensitive environments.
3. To compare the mechanical performance of the hybrid composites in dry versus wet conditions, highlighting the impact of moisture on fibre-matrix bonding and overall durability.
4. To determine the optimal fibre-to-particle ratio for achieving the best balance of mechanical strength and environmental resistance, making the composite suitable for industrial applications.

The study hypothesises that a specific ratio of bagasse fibres and groundnut shell particles will yield the best mechanical properties while minimising moisture absorption, thereby improving the overall performance of the hybrid composite. By using two natural reinforcements, the composite is expected to demonstrate improved sustainability, lower environmental impact, and reduced cost, making it a promising material for a variety of eco-friendly applications, including construction, automotive components, and packaging.

MATERIALS & METHODS

Materials

Bagasse fibres

The bagasse fibres used in this study were obtained as a by-product from a local sugar mill. The fibres were dried and ground to a uniform size to ensure consistency in reinforcement throughout the composite material.

Groundnut shell particles (GSP)

Groundnut shells were sourced from a local agricultural waste processing plant, cleaned, and ground to a fine powder using a ball mill. The particle size distribution was kept consistent to enhance uniformity in the matrix.

Phenol-formaldehyde (PF) resin

A commercial-grade thermosetting phenol-formaldehyde resin was used as the matrix material in this study due to its high mechanical strength, thermal stability, and good adhesion properties with natural fibres.

Composite Fabrication

Hybrid composites were prepared by combining the bagasse fibres and groundnut shell particles with phenol-formaldehyde resin. Varying weight fractions of groundnut shell particles (5%, 10%, 15%, and 20%) were added to the composites while keeping the bagasse fibre content constant at 30% by weight. The composites were fabricated using a hand lay-up method, followed by compression moulding at 150°C under a pressure of 5 MPa for 10 minutes to ensure proper consolidation of the layers. The samples were then allowed to cure at room temperature for 24 hours.

Water Absorption Testing

The water absorption behaviour of the hybrid composites was assessed according to ASTM D570. Samples were immersed in distilled water at room temperature for 24, 48, and 72 hours. After each immersion period, the samples were wiped with a dry cloth, weighed, and the percentage of water absorbed was calculated using the formula:

Water absorption % = ((Wet weight − Dry weight) / Dry weight)) × 100

Mechanical Testing

Tensile strength

The tensile properties of the composites were measured using a universal testing machine (UTM) according to ASTM D3039. The test was conducted at a crosshead speed of 5 mm/min, and the tensile strength and modulus were recorded.

Flexural strength

Three-point bending tests were conducted on the composites to evaluate their flexural properties. The flexural strength and modulus were determined as per ASTM D790.

Impact testing

The impact strength of the hybrid composites was evaluated using a Charpy impact tester according to ASTM D256. The tests were conducted at room temperature, and the average energy absorbed by the samples was recorded.

RESULTS & DISCUSSION

Water Absorption

The water absorption behaviour of the hybrid composites demonstrated a clear trend dependent on the percentage of groundnut shell particles (GSP). As the GSP content increased, the composites absorbed more water, which can be attributed to the hydrophilic nature of the groundnut shells. The samples with 5% GSP content exhibited the lowest water absorption (approximately 2.5%) after 72 hours, while the samples with 20% GSP content absorbed significantly more water (around 6.8%) [22-24].

This behaviour is primarily due to the cellulose content in both bagasse fibres and groundnut shells, which possess hydroxyl groups that readily form hydrogen bonds with water molecules. While bagasse fibres are also hydrophilic, their relatively high cellulose content appeared to mitigate some of the swelling that typically occurs in natural fibre composites, reducing the water absorption compared to other natural fibres such as jute or flax. The increased water absorption with higher GSP content can negatively impact the composite's mechanical properties, as will be discussed further. This behaviour suggests that the composite is unsuitable for applications requiring exposure to high levels of moisture unless measures such as fibre treatment or water-repellent coatings are implemented.

Mechanical Properties

The mechanical properties of the hybrid composites were evaluated by measuring their tensile strength, flexural strength, and impact strength. Each property exhibited different trends depending on the amount of GSP added to the composite.

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Tensile strength

The tensile strength of the hybrid composites decreased as the GSP content increased (Figure 1). The highest tensile strength of 45 MPa was observed in the 5% GSP composite, while the 20% GSP composite showed the lowest value of 32 MPa. This reduction can be explained by the fact that the GSP particles act primarily as fillers and do not significantly contribute to the tensile load-bearing capacity of the composite [25].

The presence of rigid GSP particles, while beneficial in other respects, can lead to stress concentration points within the matrix during tensile loading. This ultimately reduces the overall tensile strength of the composite, particularly when GSP content is high. The bagasse fibres, in contrast, provided much of the tensile strength, with their higher cellulose content and fibrous structure helping to reinforce the matrix. However, as GSP content increased, the beneficial effects of the bagasse fibres were somewhat diminished.

Flexural strength

In contrast to tensile strength, the flexural strength of the hybrid composites improved as GSP content increased (Figure 2). The 20% GSP composite demonstrated the highest flexural strength of 70 MPa, while the 5% GSP composite had the lowest at 55 MPa. This improvement in flexural strength can be attributed to the role of GSP particles in enhancing load transfer within the composite during bending [26].

The increased GSP content likely provided better stress distribution within the matrix, leading to improved flexural performance. The rigid nature of GSP particles allows them to resist deformation under bending stress, enhancing the composite's stiffness and strength under such conditions. This makes the GSP-reinforced composites particularly suitable for applications that require strong bending resistance, such as in construction or automotive components.

Impact strength

The impact strength of the hybrid composites also increased with higher GSP content (Figure 3). The 20% GSP composite exhibited the highest impact strength of 12 J/m, while the 5% GSP composite had impact strength of 8 J/m. The increased impact strength with higher GSP content is likely due to the particles' ability to act as crack arresters, impeding the propagation of cracks within the matrix during impact.

This improvement suggests that the GSP-reinforced composites could be advantageous for applications that involve dynamic loading or impact, where crack propagation and material toughness are critical factors. The groundnut shells particles help distribute the impact forces more effectively throughout the composite, enhancing its overall durability [27].

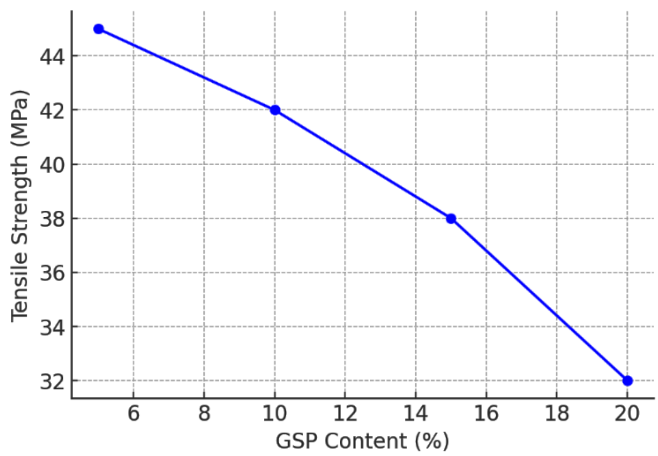

Figure 1. Tensile strength vs. GSP content.

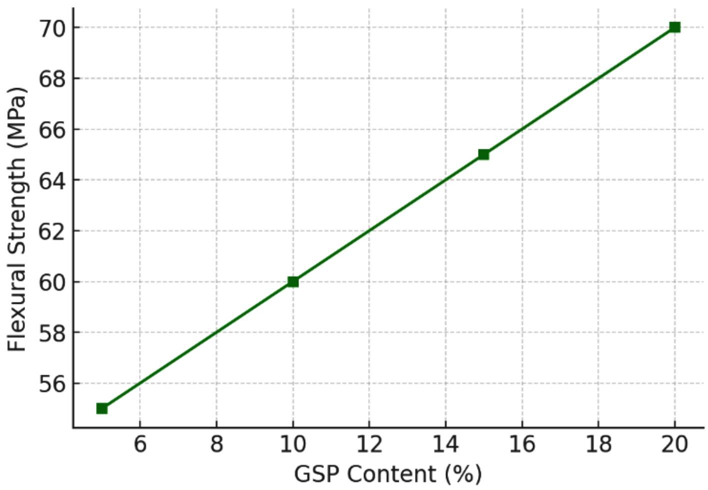

Figure 2. Flexural strength vs. GSP content.

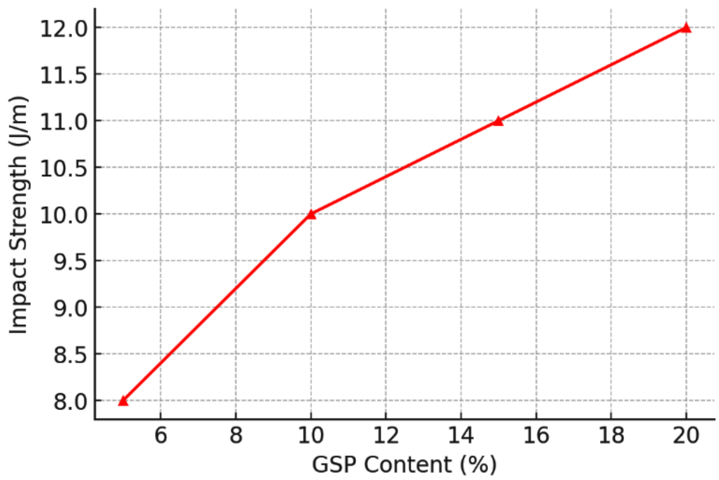

Figure 3. Impact strength vs. GSP content.

Effect of Moisture on Mechanical Properties

The graph (figure 4) shows the impact of moisture on the mechanical properties of bagasse fibre and groundnut shell particle (GSP)-reinforced hybrid composites. The mechanical properties being evaluated include tensile strength, flexural strength, and impact strength, all plotted as a function of the percentage of GSP content in the composite.

Tensile strength reduction

As the GSP content increases from 5% to 20%, the percentage reduction in tensile strength also increases. For composites with 5% GSP, the reduction in tensile strength due to moisture exposure is approximately 12%, while for composites with 20% GSP; this reduction rises to about 20%.

The increased moisture absorption in composites with higher GSP content weakens the fibre-matrix interface. Groundnut shell particles are naturally hydrophilic due to their cellulose content. With more GSP in the composite, there are more opportunities for moisture to infiltrate the matrix, causing swelling in the natural fibres and reducing the overall load-bearing capacity of the composite. This leads to a greater reduction in tensile strength as GSP content increases.

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Flexural strength reduction

The percentage reduction in flexural strength also follows a similar upward trend with increasing GSP content. At 5% GSP, the reduction in flexural strength is around 10%, while for composites with 20% GSP, the reduction is approximately 20%.

The flexural strength of the composite depends on the stiffness and bonding between the fibres and the matrix. Moisture compromises the bond by swelling the natural fibres, creating micro-cracks or delamination within the matrix, which weakens the composite's ability to resist bending. As more GSP is incorporated, the matrix becomes more susceptible to moisture-induced weakening, resulting in higher reductions in flexural strength.

Impact strength reduction

The impact strength shows a lesser degree of reduction due to moisture exposure compared to tensile and flexural properties. The reduction in impact strength increases from about 5% at 5% GSP to 10% at 20% GSP.

Impact strength measures the material's ability to absorb energy during sudden or dynamic loading. While moisture does affect the interfacial bonding, the GSP particles act as crack arresters, helping to limit the propagation of cracks caused by impact forces. This crack-arresting mechanism remains relatively effective even with moisture absorption, which explains why the reduction in impact strength is not as severe as in tensile or flexural properties

The hydrophilic nature of both bagasse fibres and GSP particles plays a significant role in the overall moisture sensitivity of the composite. Water absorption by natural fibres increases with the percentage of GSP content, leading to swelling, weakening of fibre-matrix adhesion, and degradation of mechanical properties [28].

The tensile and flexural properties are highly dependent on the integrity of the fibre-matrix interface, which is most compromised by moisture absorption. As moisture disrupts this interface, the composite's ability to bear tensile loads and resist bending forces diminishes.

Impact properties are slightly more resilient to moisture-induced degradation because they depend more on the composite's toughness and ability to resist crack propagation, which is less affected by moisture.

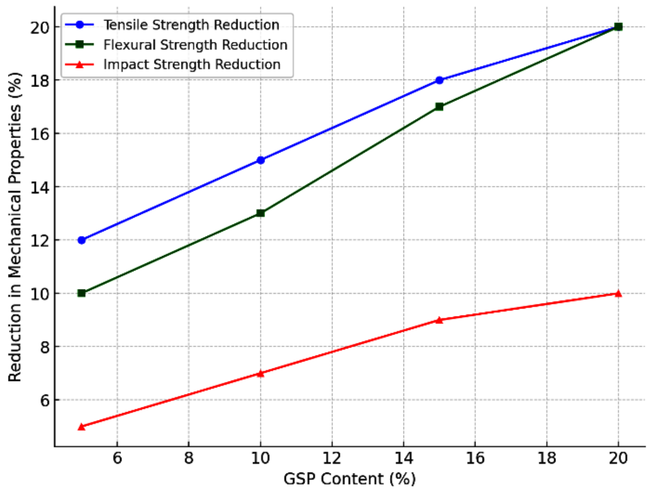

Figure 4. Effect of Moisture on Mechanical Properties vs. GSP Content.

The graph demonstrates that higher GSP content leads to greater vulnerability to moisture, particularly in terms of tensile and flexural strength. Composites with lower GSP content (around 5-10%) offer better resistance to moisture and maintain their mechanical properties more effectively after exposure [29-31].

For applications involving moisture exposure (e.g., outdoor construction, packaging), it may be necessary to limit the GSP content to minimize the loss of mechanical performance or to employ treatments (such as surface modifications or hydrophobic coatings) to enhance the moisture resistance of the composite.

Optimal Composition and Practical Applications

Based on the balance between mechanical strength and water resistance, the 10% GSP hybrid composite emerged as the optimal formulation. It demonstrated good tensile and flexural strength while maintaining a reasonable level of water absorption. This composite formulation could be suitable for industrial applications where moderate mechanical performance and environmental sustainability are essential, such as in the construction, automotive, or packaging industries.

The findings also indicate that surface modifications or coatings might be necessary to improve the water resistance of these composites, particularly if they are intended for use in moisture-exposed environments.

Implications for Long-Term Performance and Future Work

While this study primarily focuses on the immediate mechanical properties and water absorption behaviour of bagasse fibre and groundnut shell particle (GSP)-reinforced hybrid composites, it is crucial to consider the implications for long-term performance. The hydrophilic nature of natural fibres and particles, as evidenced by increased water absorption, suggests potential challenges in maintaining mechanical integrity over extended periods in humid or wet environments. Prolonged exposure to moisture could exacerbate fibre-matrix degradation, leading to reductions in tensile and flexural strength and potentially compromising the composite's reliability.

Environmental factors such as temperature fluctuations, UV radiation, and prolonged moisture exposure can significantly influence the durability of such composites. For instance, thermal cycling may induce microcracking, while UV exposure can degrade the lignin component of natural fibres, affecting their mechanical contribution.

FUTURE WORK

To evaluate the feasibility of these composites in practical applications, future studies should focus on:

- *Accelerated aging tests*: Investigating mechanical property retention under cyclic moisture and temperature conditions over extended durations.
- *Environmental stress testing:* Assessing performance under real-world conditions, including UV exposure and thermal cycling.
- *Chemical treatments*: Exploring surface modifications or matrix enhancements (e.g., hydrophobic coatings) to mitigate moisture-induced degradation.
- *Biodegradability and lifecycle analysis*: Evaluating the environmental impact and decomposition behaviour under natural weathering conditions.

This additional focus will provide a comprehensive understanding of the composites' applicability for industrial use, particularly in construction and automotive sectors where durability is critical.

CONCLUSION

It is concluded that incorporating groundnut shell particles (GSP) into bagasse fibre-reinforced composites significantly influences the mechanical properties and water absorption behaviour. The following points were arrived:

- Highest tensile strength of 45 MPa observed at 5% GSP; tensile strength decreases with higher GSP content due to stress concentration from particle fillers, reaching 32 MPa at 20% GSP.
- Flexural strength improves with increased GSP content, achieving a maximum of 70 MPa at 20% GSP, indicating enhanced load transfer and resistance to bending.
- Impact strength increases from 8 J/m at 5% GSP to 12 J/m at 20% GSP, attributed to GSP's crack-arresting ability, enhancing toughness.
- Water absorption rises with higher GSP content; composites with 20% GSP absorb 6.8% water after 72 hours compared to 2.5% for those with 5% GSP, leading to reduced mechanical performance upon moisture exposure.
- Moisture exposure results in approximately 20% reduction in tensile and flexural strengths at 20% GSP; impact strength shows a lesser reduction of about 10% due to GSP's crack-arresting function.
- A 10% GSP content offers an optimal balance between mechanical strength and water resistance, making it suitable for applications requiring moderate moisture resistance, such as automotive components and construction materials.

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