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Mechanical strength analysis of bio composite made by using micro powder made of *Prosopis cineraria* wood

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Abstract

The Present study examines the mechanical strength of bio-composites fabricated from wood powder of *Prosopis cineraria* (Khejri) and jute fiber as reinforcement inside an epoxy resin matrix. The mechanical performance of these bio-composites was assessed by altering filler content percentages (0%, 4%, 8%, 12%, 16%, and 20%) and filler particle sizes (250 microns and 500 microns) under standard and carbonate conditions. Tensile strength and impact energy assessments were performed to evaluate the effects of filler content, particle size, and filler type on the mechanical characteristics of the composites. The tensile strength tests reveal that composites with 12% filler and a particle size of 250 microns had the maximum tensile strength, measuring 33.4 MPa under normal settings and 34.8 MPa under carbonate conditions. An increase in filler content over 12% resulted in a reduction in mechanical strength due to filler agglomeration, which decreased stress transfer efficiency. The composites with 250-micron particles consistently demonstrated superior tensile and impact strengths compared to those with 500-micron particles, due to the increased surface area of the smaller particles. Comparative analysis of normal and carbonate conditions demonstrated that carbonate fillers offered superior reinforcement owing to their increased density and enhanced matrix-filler interaction, leading to augmented tensile and impact strength. These findings provide significant insights into the development of bio-composites for structural applications, namely in improving their mechanical strength and durability.

Keywords*:* Epoxy Resin; Natural microparticle; Natural fiber sheet; Composite; DOE

1. Introduction

Polymer matrix composites (PMCs) have emerged as a transformative category of materials with substantial uses in both industrial and domestic sectors. Their unique characteristics, including low weight, high strength-to-weight ratio, durability, and cost efficiency, render them appropriate for many applications. Furthermore, these materials have exceptional thermal and chemical resistance, enhancing their increasing demand in sectors like as aerospace, automotive, and renewable energy. PMCs are commonly utilized in essential components such as airplane structures, automobile body panels, wind turbine blades, and sports equipment, where their low density and great mechanical strength provide significant benefits. The adaptability of polymer composites is attributed to their capacity to be customized for certain specifications, attainable via various reinforcing methods. Fiber reinforcement is a highly effective method for augmenting the strength and mechanical characteristics of polymer composites. Upon the application of a load to a fiber-reinforced composite, the fibers accommodate a substantial fraction of the load, therefore redistributing stress from the polymer matrix. This allows the composite material to withstand greater loads and improves its overall mechanical performance. The orientation and kind of fibers employed—be it carbon, glass, or natural fibers are pivotal in influencing the composite's ultimate qualities, including flexibility, toughness, and load-bearing capacity.

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In addition to fiber reinforcement, the integration of particles into the polymer matrix offers an effective approach for enhancing the particular characteristics of composites. Composites loaded with particles are progressively used in specific applications that necessitate distinctive characteristics such as thermal stability, magnetic qualities, or electrical insulation. Incorporating particles can augment the composite's resistance to thermal expansion or boost its dielectric characteristics, rendering it appropriate for electronic applications and high-temperature settings. Particle reinforcement, similar to fiber reinforcement, enhances the capabilities of PMCs, enabling their adaptation to a wider array of industrial and technological applications. The polymer matrix in these composites is the most susceptible component of the material. The matrix is vulnerable to many degradation mechanisms, including mechanical stress, temperature cycling, chemical exposure, and moisture absorption. The selection of the appropriate matrix material either thermosetting or thermoplastic is essential for guaranteeing long-term performance. Thermoplastic matrices are preferred because to their durability, impact resistance, and recyclability, as they can be re-melted and reformed. Conversely, thermosetting matrices, upon curing, provide superior thermal stability and chemical resistance; nevertheless, they are often more brittle and less flexible, which restricts their application in dynamic or impact-sensitive settings.

In the design of polymer matrix composites, the selection between continuous and discontinuous fiber reinforcement is a crucial factor. Continuous fibers impart directional strength, rendering the composite anisotropic, with enhanced strength along the fiber axis. This attribute is crucial for applications necessitating excellent performance in particular load orientations, such as in aircraft and automotive components. In contrast, discontinuous fibers, placed randomly inside the matrix, provide isotropic characteristics to the composite, leading to consistent mechanical performance in all directions. This homogeneity is advantageous in applications requiring consistent stress distribution across the material. The advancement of composite materials is anticipated to improve the qualities of polymer matrix composites (PMCs) through advances in polymer matrices, reinforcing techniques, and the integration of nanoparticles. These developments will probably result in more efficient, durable, and flexible materials, broadening their applications and enhancing their performance in essential industries.

2. Literature Review

The investigation of polymer matrix composites (PMCs) has attracted heightened interest owing to the adaptability and superior performance provided by diverse reinforcing methods, particularly in scenarios necessitating elevated mechanical strength and durability. A multitude of researchers have investigated many facets of PMCs, providing significant insights into their mechanical properties, production methods, and hybridization capabilities. Karuppiah (2016) created a prediction model utilizing finite element micromechanics to evaluate the stress relaxation characteristics of woven composites, highlighting the impact of weave architecture on mechanical performance. This study emphasizes the significance of the structural design of fiber reinforcements in customizing composite characteristics for particular applications. He et al. (2020) enhanced the comprehension of hybrid composites by examining the mechanical characteristics of carbon fiber and high-strength polyimide fiber-reinforced composites. Their research revealed a substantial enhancement in both strength and modulus through the amalgamation of various fibers, indicating the promise of hybrid composites for applications necessitating superior mechanical performance, such as in the aerospace and automotive sectors. Yu et al. (2015) investigated hybrid composites, particularly those reinforced with intertwined carbon and glass fibers. Their research presented the notion of pseudo-ductility in composites using highly aligned discontinuous fibers, demonstrating the capacity to improve ductility while maintaining strength.

Marques (2011) conducted a comprehensive analysis of the production procedures for fibrous materials reinforced composites, elucidating several manufacturing methods that enhance the performance and cost-effectiveness of composites in civil engineering applications. Kuppusamy et al. (2020) highlighted sophisticated production methods for aerospace composites, concentrating on the accuracy necessary for fabricating high-performance composite structures. The investigation of particulate-filled composites has accelerated, as evidenced by Choudhary et al. (2019), who illustrated the capability of waste marble dust to improve the thermomechanical and erosive wear characteristics of glass fiber-reinforced composites. This underscores the increasing trend of using waste resources to produce environmentally sustainable and economically viable composites.

3. Materials and Methods

In this study, the materials selected for the development of biodegradable composites include Khejri (*Prosopis cineraria* and polyester resin (epoxy resin). These materials were chosen based on their mechanical properties, ecological sustainability, and potential to reinforce polymer-based composites. The focus of this section is to describe the materials and methods used for the fabrication of the composites, as well as their significance in the context of biodegradable composite development.

3.1. Khejri (*Prosopis cineraria*) as Filler Material

Khejri, sourced from the *Prosopis cineraria* tree, serves as a natural filler material in this research. Native to the arid regions of India, Khejri is highly valued for its ecological and economic benefits. The tree is known for its resilience in harsh climates and plays a key role in preventing soil erosion. The filler particles obtained from the tree provide strength and durability to the composite material. Khejri resin, also referred to as sal gum, contains significant fat content (12–19%) and is often used in the production of varnishes and lacquers. Its biodegradable nature makes it a suitable choice for environmentally friendly composite applications. The harvested Khejri filler particles were refined into a fine powder and incorporated into the composite mix, contributing to both the mechanical performance and sustainability of the final product.

3.2. Polyester Resin (Epoxy Resin)

The polymer matrix used in this study is polyester resin, specifically epoxy resin. This type of resin is known for its excellent adhesion, mechanical strength, and chemical resistance, making it a suitable binder for the natural fibers and filler materials used. It provides the composite with a robust matrix that ensures durability and long-term performance. The composite fabrication process involved the mixing of these materials in specific proportions, followed by curing and testing for mechanical properties. Each material's role in enhancing the composite's strength, biodegradability, and durability were carefully analyzed and optimized.

4. Result and discussion

This section presents a detailed analysis of the mechanical strength of bio-composites made by mixing *Prosopis cineraria* (Khejri) wood waste powder and carbonate powder with an epoxy resin (ER) matrix. Tensile and impact strength tests were performed on composites with varying filler content percentages (0%, 4%, 8%, 12%, 16%, and 20%) and two different particle sizes (250 microns and 500 microns). The results of these tests provide insights into the mechanical behavior of the bio-composites under different conditions and highlight how filler content, particle size, and filler type influence the composite’s properties.

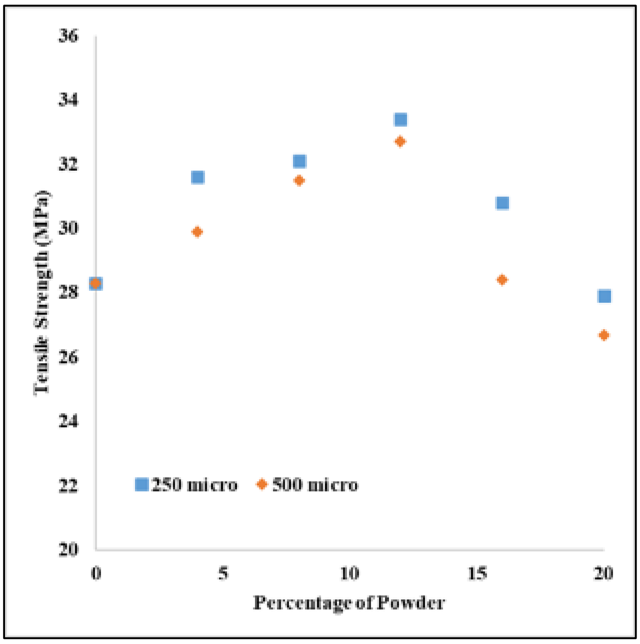

Figure 1 Tensile Strength of Composite made with Powder of Khejri Wood (Normal)

Tensile strength experiments performed on bio-composites utilizing standard *Prosopis cineraria* wood waste powder as a filler demonstrated a distinct correlation between filler quantity and the tensile qualities of the material. The initial tensile strength of the unfilled pure epoxy composite was measured at 28.3 MPa. The use of 4% filler with a particle size of 250 microns resulted in an increase in tensile strength to 31.6 MPa, signifying increased mechanical reinforcing. With the filler percentage rising to 8% and 12%, the tensile strength progressively enhanced, attaining 32.1 MPa and a maximum of 33.4 MPa, respectively. The increased tensile strength at 12% filler content is due to the enhanced dispersion of filler particles inside the epoxy matrix, facilitating superior load transmission between the matrix and the filler.

Nonetheless, additional increments in the filler content resulted in a reduction of tensile strength. At 16% filler, the tensile strength decreased to 30.8 MPa, and at 20%, it declined to 27.9 MPa. The reduction can be attributed to the propensity of filler particles to agglomerate at elevated concentrations, leading to unequal stress distribution and the emergence of weak areas in the composite. A comparable trend was noted for the 500-micron particle size samples, but with somewhat reduced tensile strength values. The tensile strength of pure epoxy was 28.3 MPa, rising to 29.9 MPa with 4% filler and reaching a maximum of 32.7 MPa with 12% filler content. The diminished tensile strength at elevated filler content (16% and 20%) for the 500-micron samples is again ascribed to filler agglomeration, which reduces the load-bearing capability of the composite.

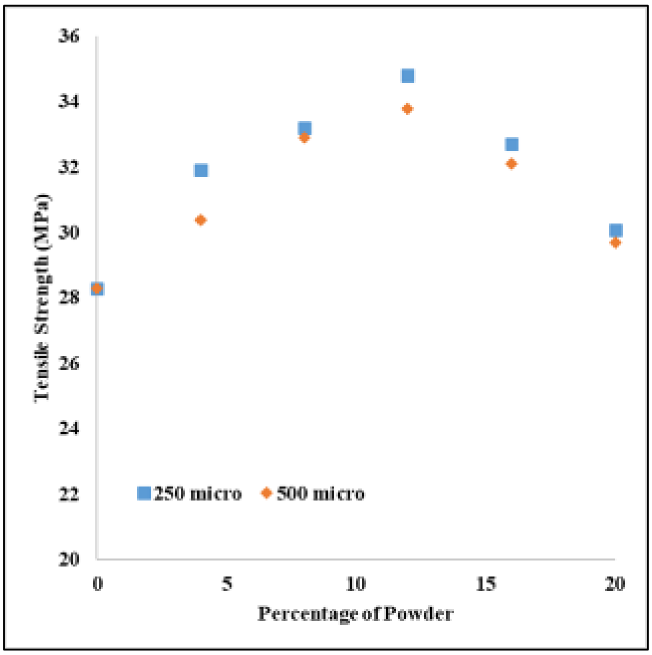

Figure 2 Tensile Strength of Composite made with Powder of Khejri Wood (Carbonate)

The tensile strength results for bio-composites utilizing carbonate powder in place of wood waste exhibited comparable tendencies, but with generally elevated tensile strength values. The tensile strength for the 250-micron particle size rose from 28.3 MPa in the pure epoxy composite to 31.9 MPa with 4% filler and 33.2 MPa with 8% filler. The maximum tensile strength of 34.8 MPa was observed with a filler concentration of 12%. As filler percentage exceeded 12%, the tensile strength decreased to 32.7 MPa at 16% and 30.1 MPa at 20%. The results indicate that carbonate powder offers superior reinforcement compared to conventional wood waste, presumably owing to its greater density and enhanced bonding characteristics with the epoxy matrix. The 500-micron carbonate powder composites demonstrated superior tensile strength compared to the standard wood waste samples, with a maximum strength of 33.8 MPa at 12% filler content. Nonetheless, similar to conventional wood waste composites, tensile strength diminished with increased filler content owing to agglomeration effects.

The impact strength of the bio-composites, quantified in J/m^2, exhibited a trend analogous to that of tensile strength. The impact strength of the 250-micron particle size composites rose from 3107 J/m^2 for the pure epoxy composite to 3217 J/m^2 at 4% filler, 3297 J/m^2 at 8% filler, and reached a maximum of 3328 J/m^2 at 12% filler content. The enhancement in impact strength with reduced filler concentration is ascribed to the homogeneous distribution of filler particles, which augments the composite's energy absorption capacity during impact. At 16% and 20% filler content, the impact strength diminished to 3267 J/m^2 and 3008 J/m^2, respectively, presumably due to filler agglomeration resulting in stress concentration spots.

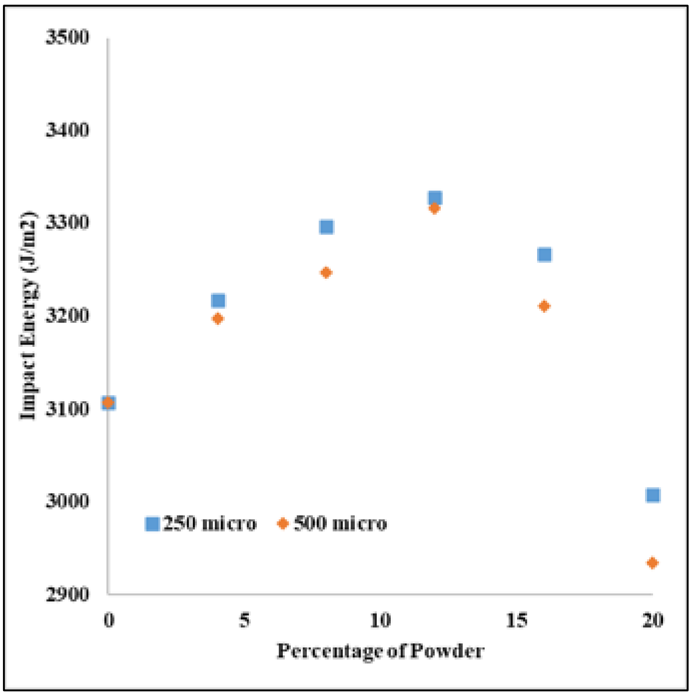

Figure 3 Impact Energy of Composite made with Powder of Khejri Wood (Normal)

In the samples with a particle size of 500 microns, a comparable pattern was noted, with the impact strength reaching a peak of 3316 J/m^2 at 12% filler content, thereafter decreasing with elevated filler percentages. The diminished impact strength of the 500-micron samples relative to the 250-micron counterparts aligns with the decreased surface area of bigger particles, which restricts effective filler-matrix adhesion.

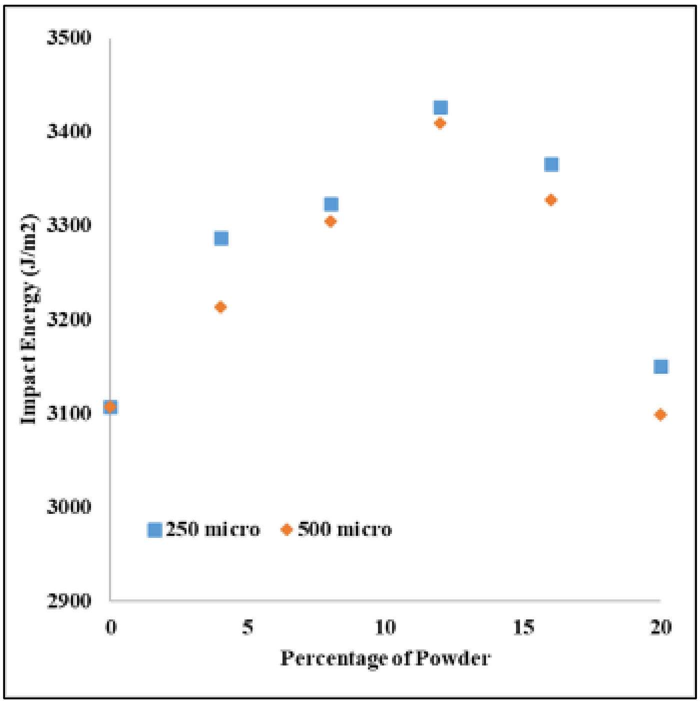

Figure 4 Impact Energy of Composite made with Powder of Khejri Wood (Carbonate)

The impact strength of the carbonate powder composites was generally higher than that of the normal wood waste composites. For the 250-micron particle size, the impact strength increased from 3107 J/m^2 to 3287 J/m^2 at 4% filler, 3324 J/m^2 at 8%, and peaked at 3427 J/m^2 at 12% filler. This suggests that carbonate powder enhances the composite's toughness more effectively than normal wood waste. However, as filler content increased beyond 12%, the impact strength decreased to 3366 J/m² at 16% filler and 3151 J/m² at 20%, again due to filler agglomeration. The 500-micron carbonate powder composites followed a similar pattern, with the maximum impact strength of 3409 J/m² recorded at 12% filler content. However, as with other samples, the impact strength decreased at higher filler contents, emphasizing the importance of optimal filler dispersion to maintain the composite's mechanical integrity.

The mechanical strength of bio-composites made with *Prosopis cineraria* wood waste and carbonate powder is significantly influenced by the filler content, particle size, and filler type. The optimum mechanical performance was achieved at 12% filler content, with 250-micron particle size providing better tensile and impact strength than 500-micron particle size. Carbonate powder demonstrated superior reinforcement capabilities compared to normal wood waste, offering higher tensile and impact strength. However, excessive filler content beyond 12% resulted in diminished performance due to filler agglomeration, highlighting the need for careful optimization of filler content in bio-composite formulations for structural applications.

5. Conclusion

The examination of the mechanical strength of bio-composites composed of *Prosopis cineraria* (Khejri) wood powder and jute fiber provides critical insights into the influence of filler quantity, particle size, and filler type on the tensile and impact characteristics of the composites. The tensile strength research demonstrates that filler content significantly influences the mechanical performance of the composite. Composites with 12% filler content and 250-micron particle size consistently exhibited the best tensile strength, attaining 33.4 MPa under standard settings and 34.8 MPa under carbonate conditions. The enhancement in tensile strength at 12% filler content is due to the appropriate distribution of the filler material inside the epoxy matrix, facilitating efficient load transmission and mechanical interlocking. As the filler percentage rose to 16% and 20%, the tensile strength diminished due to the agglomeration of filler particles, which disrupted the homogeneous distribution of stress and decreased the bonding effectiveness between the filler and the matrix. This aggregation resulted in vulnerabilities within the composite structure, causing a reduction in mechanical performance. The particle size markedly affected the mechanical strength, with composites composed of 250-micron particles regularly surpassing those constructed from 500-micron particles. The increased surface area of smaller particles improved the adhesion between the filler and matrix, leading to higher load transmission and superior tensile characteristics.

The comparison of normal and carbonate conditions demonstrated that carbonate powder offered enhanced reinforcement to the epoxy matrix relative to standard wood waste powder. Composites filled with carbonate exhibited enhanced tensile and impact strength, presumably attributable to the carbonate's greater density and improved interfacial adhesion with the epoxy matrix. The maximum tensile strength was attained at 12% filler content for both normal and carbonate composites, with a particle size of 250 microns producing the most favorable outcomes. Past this threshold, mechanical performance declined due to increased filler agglomeration. The 12% filler composites had the greatest energy absorption capability for impact strength, corroborating the results from the tensile strength tests. Similar to tensile strength, an increased filler content over 12% led to a decline in impact strength due to the agglomeration effect, which compromised the matrix-filler interface and lowered the composite's capacity to absorb impact energy. The bio-composites with carbonate powder demonstrated enhanced impact strength relative to those produced with conventional wood waste, hence reinforcing the assertion that carbonate fillers offer superior mechanical reinforcement. This work offers significant insights into the mechanical performance of bio-composites and underscores the necessity of adjusting filler volume, particle size, and filler type to attain enhanced mechanical characteristics. The findings have practical significance for the design and development of bio-composites in structural applications, namely in improving the tensile and impact strength of sustainable materials.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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