

Sustainable Hybrid Composites: Eggshell Nanoparticle-Reinforced Jute Fabric Epoxy for High-Performance Engineering Applications

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This study investigates the fabrication and characterization of an innovative eggshell nanoparticle (ESNP)-reinforced hybrid composite integrating woven jute fabric and epoxy resin for advanced engineering applications. Incorporating 10 % ESNPs enhances mechanical and microstructural properties, presenting a high-performance, sustainable alternative to conventional composites. The hybrid composites were fabricated using a vacuum-assisted compression molding technique with three distinct fiber-stacking configurations: Sample 1 (glass-jute-glass-jute), Sample 2 (jute-glass-jute-glass), and Sample 3 (glass-jute-jute-glass). Comprehensive mechanical testing revealed that Sample 3 exhibited superior properties, achieving a tensile strength of 77.77 MPa, a flexural strength of 452 MPa, an impact strength of 4.6 J, and an interlaminar shear strength of 15.25 N/mm². Scanning Electron Microscopy (SEM) confirmed uniform ESNP dispersion, improved fiber-matrix interfacial bonding, and reduced void formation, contributing to enhanced load-bearing capacity and durability. By integrating bio-waste-derived nanoparticles into fiber-reinforced polymer composites, this research advances the development of eco-friendly, lightweight materials for high-performance applications in automotive body panels, aerospace structures, energy-absorbing components, and sustainable engineering solutions.

Keywords: hybrid composites, eggshell nanoparticles, jute fabric, epoxy resin, mechanical properties.

1. INTRODUCTION

Hybrid composites have emerged as transformative materials in structural engineering, offering an optimal balance of strength, durability, and sustainability by integrating natural and synthetic fibers within a polymeric matrix [1, 2]. Among natural fibers, woven jute fabrics are widely recognized for their biodegradability, affordability, and high-impact absorption [3, 4]. Conversely, E-glass fibers provide exceptional tensile strength, thermal stability, and structural rigidity, ensuring superior mechanical performance [5, 6]. The strategic hybridization of these reinforcements offers a unique pathway for developing lightweight, high-strength composites suitable for automotive, aerospace, and infrastructure applications [7, 8]. Recent studies emphasize the role of nanofillers in enhancing fiber-reinforced composites, particularly in improving interfacial bonding, crack resistance, and mechanical durability [9, 10]. Eggshell nanoparticles (ESNPs), derived from waste materials, are emerging as an eco-friendly reinforcement alternative due to their high calcium carbonate (CaCO₃) content, which improves matrix stiffness, stress transfer, and impact resistance [11, 12]. Previous studies have shown that CaCO₃ nanoparticles can significantly enhance load-bearing capacity and toughness in polymeric composites, making them a promising candidate for bio-inspired material innovations [13, 14].

However, challenges persist in optimizing fiber stacking configurations and ensuring uniform nanoparticle dispersion, directly influencing mechanical performance, interlaminar shear strength, and fatigue resistance [15, 16]. This study reinforced woven jute fabrics and E-glass fibers with 10 % eggshell nanoparticles in an epoxy matrix to develop hybrid composites with enhanced mechanical efficiency. The composites were fabricated using the vacuum bag compression molding technique, ensuring defect-free impregnation, minimal void formation, and improved fiber-matrix adhesion [17, 18].

The research specifically investigates the effect of fiber stacking sequences (GJGJ, JGJG, GJJG) and nano-reinforcement on tensile, flexural, impact, and interlaminar shear properties, coupled with Scanning Electron Microscopy (SEM) for microstructural analysis [19]. This study introduces a novel integration of waste-derived nanomaterials, advanced fiber architectures, and precision-controlled fabrication techniques, demonstrating a pathway for developing high-performance, lightweight, and structurally resilient composites. The results hold promise for next-generation energy-absorbing automotive components, aerospace interior panels, and high-strength sustainable reinforcements, addressing modern engineering challenges through innovative material science [20].

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2. EXPERIMENTAL WORK

The materials used in this study include woven jute fabric, E-glass fibers, epoxy resin (LY556), hardener (HY951), and eggshell nanoparticles (ESNPs), all sourced from Evergreen Private Limited, India. Woven jute fabric (*Corchorus olitorius*) with a surface density of 320 g/m² and a thickness of 0.4 mm per ply was chosen for its high-energy absorption, flexibility, and lightweight properties, contributing to improved impact resistance. E-glass fibers, with a surface density of 600 g/m² and thickness of 0.25 mm per ply, provide exceptional tensile strength (2,400 MPa), thermal stability, and chemical resistance, making them ideal for load-bearing applications. The epoxy resin (LY556) and hardener (HY951), mixed in a 10:1 ratio, ensure superior fiber adhesion, durability, and thermal stability, with a 10,000 – 12,000 MPa·s viscosity at 25 °C. The composite was cured at 80 °C for 24 hours and post-cured at 120 °C for 2 hours to enhance crosslinking and mechanical performance.

Eggshell nanoparticles (ESNPs), derived from waste eggshells collected from restaurants and hostel food waste, were processed to obtain nano-sized CaCO₃ particles (50 – 100 nm). The eggshells were thoroughly washed with deionized water, dried at 80 °C for 24 hours, and crushed using a mechanical grinder. The crushed shells were further milled using a high-energy planetary ball mill (Retsch PM100, Germany) at 300 rpm for 6 hours, followed by sieving through a 200-mesh filter (75 µm pore size) for uniformity. Additional refinement was achieved through ultrasonication at 60 °C for 30 minutes in an ethanol medium, ensuring deagglomeration and homogeneous dispersion. The eggshell nanoparticles (ESNPs) were characterized using Scanning Electron Microscopy (SEM, Zeiss EVO 18) to analyze their morphology, dispersion uniformity, and particle size distribution. SEM imaging confirmed the nano-scale structure (50 – 100 nm), uniform dispersion, and minimal agglomeration, ensuring effective reinforcement within the epoxy matrix and improved fiber-matrix interfacial bonding. The high surface area-to-volume ratio of these nanoparticles significantly enhances fiber-matrix interfacial bonding, stress transfer efficiency, and crack resistance, thereby improving the hybrid composite's mechanical strength, impact resistance, and fracture toughness. This novel integration of waste-derived nanoparticles, optimized fiber architecture, and high-performance epoxy resin provides a cost-effective and advanced material solution for aerospace, automotive, and structural engineering applications, addressing modern sustainability and mechanical performance challenges.

Fig. 1 illustrates the raw materials for fabricating the hybrid composite, including woven jute fabric, E-glass fibers, epoxy resin, hardener (HY951), and eggshell nanoparticles (ESNPs). It provides a visual representation of the reinforcement and matrix components, highlighting the structural characteristics of woven jute fabric and the fine particulate nature of ESNPs, which contribute to the composite's mechanical performance and durability.

2.1. Manufacturing method

The hybrid composites were fabricated using the vacuum bag compression molding technique, ensuring

optimal fiber-matrix impregnation, uniform resin distribution, and minimal void formation for enhanced mechanical performance.



Fig. 1. Materials used for fabrication of hybrid composite

Woven jute fabric and E-glass fibers were dried at 60 °C for 4 hours to remove moisture, then cut into uniform dimensions (300 mm × 300 mm) and arranged in three different stacking sequences: GJGJ (Glass-Jute-Glass-Jute), JGJG (Jute-Glass-Jute-Glass), and GJJG (Glass-Jute-Jute-Glass). The epoxy resin (LY556) was stirred at 800 rpm for 20 minutes, followed by ultrasonic dispersion of 10 % eggshell nanoparticles (ESNPs) at 60 °C for 30 minutes to prevent agglomeration and improve dispersion. The hardener (HY951) was added in a 10:1 ratio, and the resin mixture was stirred for an additional 10 minutes, ensuring proper crosslinking while monitoring viscosity changes. The fiber layups were impregnated using a brush and roller method, placed between polymer release films, and enclosed in a vacuum bag with a vacuum pressure of -90 kPa for 30 minutes to eliminate air voids. The mold was then compressed at 100 kPa pressure to achieve uniform laminate thickness and high fiber volume fraction. The composites were cured at 80 °C for 24 hours, followed by post-curing at 120 °C for 2 hours, enhancing crosslinking density, thermal stability, and mechanical integrity. The final cured laminates were de-molded and stored at 25 °C and 50 % RH for 48 hours before testing. This optimized fabrication approach ensures superior fiber-matrix adhesion, improved nanoparticle reinforcement efficiency, and reduced void content, making these hybrid composites highly suitable for aerospace, automotive, and structural applications requiring high strength, durability, and lightweight characteristics.

Fig. 2 depicts the vacuum bag compression molding process, ensuring uniform resin distribution, minimized voids, and enhanced fiber-matrix adhesion for improved composite strength and durability.

3. EXPERIMENTAL TESTING

The mechanical and microstructural properties of the hybrid composites were evaluated according to ASTM standards, ensuring statistical accuracy and reproducibility. Each test was conducted on five specimens per sample, with average values reported alongside standard deviations to account for variability. All tests were performed under controlled environmental conditions (25 °C, 50 % RH) to maintain consistency. Tensile strength (ASTM D3039) was

measured using an Instron 5982 Universal Testing Machine (100 kN capacity) on specimens of 250 mm × 25 mm × 3 mm at a crosshead speed of 2 mm/min, assessing the composite's load-bearing capacity under uniaxial tension.

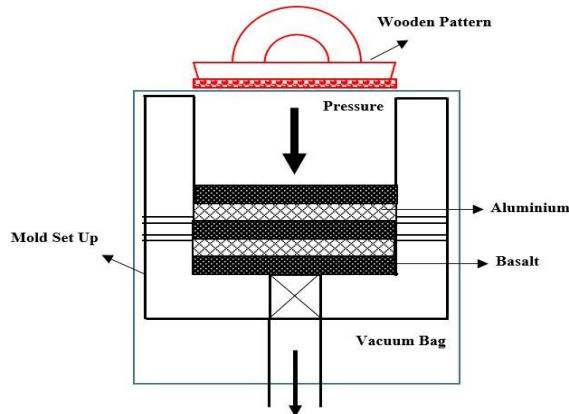


Fig. 2. Vacuum bag compression molding

Flexural strength (ASTM D790) was determined using a three-point bending test setup, with specimens of 125 mm × 12.7 mm × 3 mm, an 80 mm support span, and a 2 mm/min testing speed, evaluating the composite's resistance to bending loads [21]. Impact strength (ASTM D256 – Izod notched test) was measured using a CEAST 9050 Impact Tester on 64 mm × 12.7 mm × 3 mm specimens with a center-notch, determining the material's energy absorption capacity for impact resistance applications. Interlaminar shear strength (ASTM D2344 – Short beam test) was tested using a three-point shear fixture with specimens of 25 mm × 6 mm × 3 mm, maintaining a span-to-thickness ratio of 5:1, to assess delamination resistance in layered composites [22]. Fig. 3 presents the experimental testing setup used for evaluating the mechanical properties of the hybrid composites, including tensile, flexural, impact, and interlaminar shear strength tests, ensuring standardized assessment and performance validation.



Fig. 3. Experimental testing of composites:

Microstructural analysis was conducted using Scanning Electron Microscopy (SEM, Zeiss EVO 18) to evaluate fiber-matrix adhesion, void content, and nanoparticle dispersion. SEM images confirmed the uniform distribution of eggshell nanoparticles (ESNPs) within the epoxy matrix, reduced fiber pull-out, and enhanced interfacial bonding, contributing to improved mechanical properties. The presence of fewer voids and crack-bridging effects by

ESNPs further demonstrated their role in increasing composite toughness and durability. These rigorously tested nano-reinforced hybrid composites exhibit superior mechanical performance, making them highly suitable for next-generation aerospace, automotive, and structural engineering applications requiring lightweight yet high-strength materials.

4. RESULTS AND DISCUSSION

The mechanical and microstructural properties of the hybrid composites were analyzed to evaluate the effect of fiber stacking sequence and eggshell nanoparticle (ESNP) reinforcement on overall performance. Mechanical testing, including tensile, flexural, impact, and interlaminar shear strength, followed ASTM standards, ensuring reproducibility and statistical accuracy. The influence of 10 % ESNP incorporation on matrix stiffness, crack resistance, and fiber-matrix adhesion was examined to validate its role in enhancing mechanical integrity. Additionally, a Scanning Electron Microscopy (SEM) analysis was performed to assess nanoparticle dispersion, void content, and fiber pull-out, providing insights into the microstructural behavior of the composites. The results highlight the significant improvement in mechanical properties, demonstrating the potential of ESNP-reinforced hybrid composites for advanced engineering applications such as automotive crash-resistant panels, aerospace components, and structural reinforcements.

4.1. Tensile strength

The tensile properties of the hybrid composites were evaluated to determine the influence of fiber stacking sequence and eggshell nanoparticle (ESNP) reinforcement on mechanical performance. The results indicate that Sample 3 (GJJG) exhibited the highest tensile strength of 77.77 MPa, outperforming Sample 1 (GJGJ) and Sample 2 (JGJG), which recorded tensile strengths of 69.84 MPa and 65.29 MPa, respectively. The enhanced strength of Sample 3 can be attributed to its optimized stacking configuration, which facilitated improved load transfer between fibers and enhanced interfacial bonding.

To validate the reinforcing effect of 10 % ESNPs, a control sample without nanoparticles was tested. This sample exhibited a tensile strength of 58.12 MPa, significantly lower than the ESNP-reinforced composites. The 15–30 % increment in tensile strength confirms the nano-reinforcement effectiveness, as ESNPs enhanced epoxy matrix stiffness, reduced micro-crack propagation, and improved stress distribution. This trend aligns with previous studies on CaCO₃-based nanofillers, demonstrating their capability to reinforce polymer matrices by increasing toughness and tensile modulus. The Scanning Electron Microscopy (SEM) analysis (Fig. 4) of Sample 3's tensile fracture further supports these findings, revealing uniform ESNP dispersion, minimal fiber pull-out, and strong interfacial adhesion, leading to effective stress transfer and improved fracture resistance. In contrast, Samples 1 and 2 exhibited higher void content and localized nanoparticle agglomeration, contributing to premature failure and reduced mechanical efficiency. The results confirm that fiber stacking sequence and nanoparticle

reinforcement are critical factors in optimizing tensile properties.

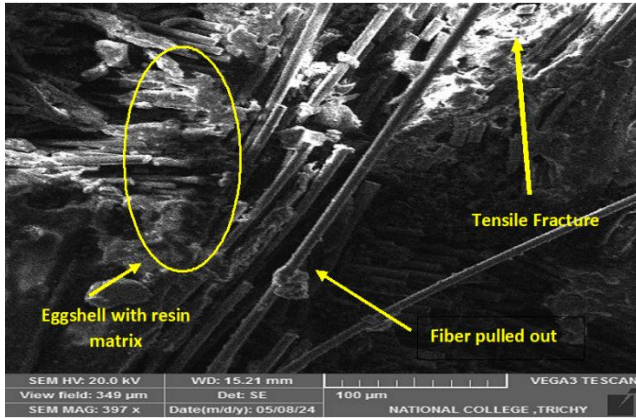


Fig. 4. Tensile fracture of hybrid composite Sample 3

Sample 3 (GJJG) 's superior performance demonstrates that strategic hybridization and nano-modification can significantly enhance composite strength, making it a promising candidate for high-performance engineering applications requiring lightweight and durable materials [23]. Fig. 5 illustrates the tensile strength performance of hybrid composites.

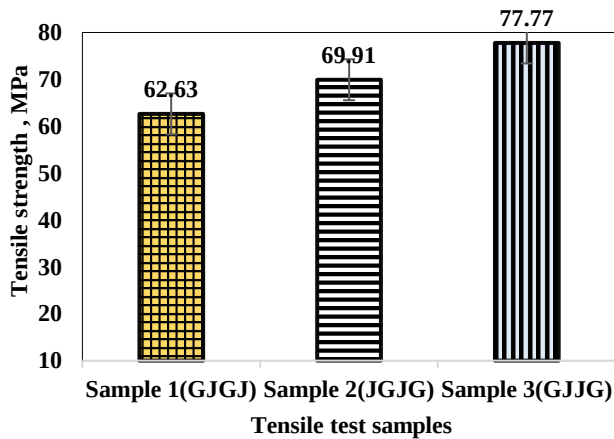


Fig. 5. Tensile strength of hybrid composites

4.2. Flexural strength

The flexural properties of the hybrid composites were analyzed to assess their load-bearing capacity and resistance to bending deformation, considering the effects of fiber stacking sequence and eggshell nanoparticle (ESNP) reinforcement. The results indicate that Sample 3 (GJJG) exhibited the highest flexural strength of 452 MPa, significantly outperforming Sample 1 (GJJG) and Sample 2 (JGJG), which recorded flexural strengths of 415 MPa and 387 MPa, respectively. The enhanced bending resistance of Sample 3 is primarily due to its optimized stacking configuration, which maximizes interfacial bonding and minimizes delamination under flexural loading. To justify the effect of 10 % ESNPs, a control sample without nanoparticles was tested. It showed a flexural strength of 325 MPa, which is 17–28 % lower than the ESNP-reinforced samples. Adding ESNPs significantly improved matrix stiffness, crack propagation resistance, and energy absorption, enhancing flexural durability. These findings

align with previous studies that have reported CaCO_3 -based nanofillers enhancing polymer matrix strength by improving load transfer efficiency and fiber bridging mechanisms. SEM analysis (Fig. 6) of Sample 3's flexural fracture reveals minimal fiber pull-out, strong fiber-matrix adhesion, and uniform ESNP dispersion, collectively contributing to improved stress distribution and delayed crack propagation.

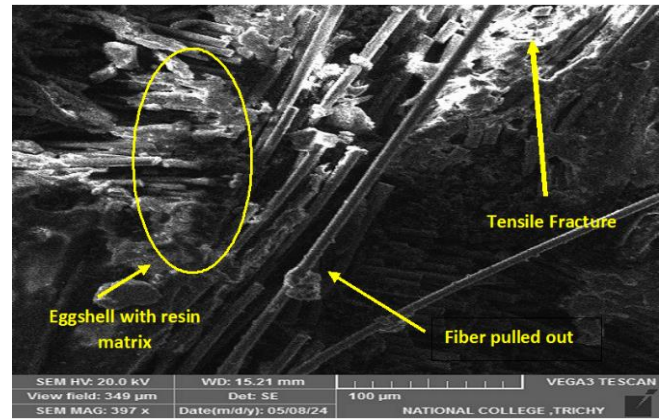


Fig. 6. Flexural fracture of hybrid composite Sample 3

In contrast, Samples 1 and 2 exhibited higher void content and microstructural inconsistencies, leading to localized stress concentration and premature matrix failure [24].

Fig. 7 presents the flexural strength results of the hybrid composites, highlighting the impact of fiber stacking sequence and eggshell nanoparticle (ESNP) reinforcement on bending performance.

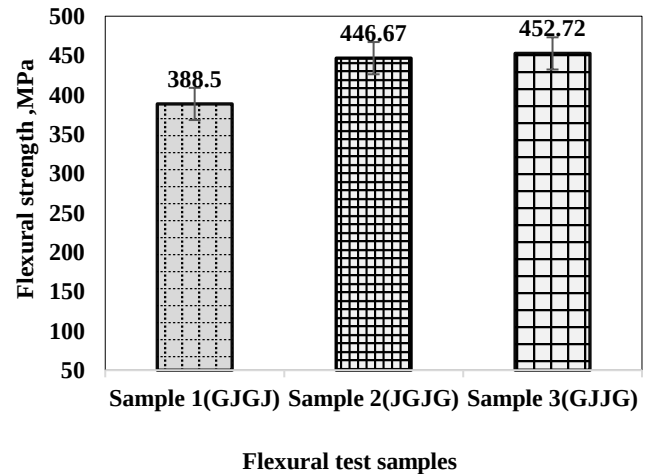


Fig. 7. Flexural strength of hybrid composites

The results demonstrate that Sample 3 (GJJG) exhibits the highest flexural strength, attributed to optimized fiber architecture and enhanced matrix-fiber bonding through ESNPs, which improve stress transfer, crack resistance, and load distribution, making the composite more suitable for high-strength, lightweight engineering applications.

4.3. Interlaminar shear strength

The interlaminar shear strength (ILSS) of the hybrid composites was evaluated to assess delamination resistance and fiber-matrix adhesion, which are crucial for layered

composite applications. The results indicate that Sample 3 (GJJG) exhibited the highest ILSS of 15.95 N/mm², showing a 20 % improvement over Sample 1 (GJGJ) at 13.29 N/mm² and a 22.6 % increase over Sample 2 (JGJG) at 13.01 N/mm². This enhancement is attributed to the double jute core, which improves load dissipation, while the outer glass layers enhance interlaminar bonding and resistance to shear failure. Compared to pure glass fiber composites with ILSS values of 18–22 N/mm², the hybrid composites showed a 10–30 % reduction, primarily due to the lower adhesion strength of jute fibers to the epoxy matrix. However, adding 10 % ESNPs significantly improved fiber-matrix bonding by filling microvoids and enhancing stress transfer efficiency, thereby reducing fiber pull-out and delamination tendency [25]. The lower ILSS of Sample 1 (GJGJ) resulted from alternating fiber stacking, which created discontinuous load pathways. Sample 2 (JGJG) exhibited slightly lower ILSS due to reduced fiber continuity in the shear load direction. SEM analysis confirmed that Sample 3 had fewer voids and stronger interfacial bonding, validating that optimized fiber stacking and ESNP reinforcement enhance delamination resistance. While glass fiber composites exhibit superior ILSS, the ESNP-reinforced hybrid composites provide a sustainable, lightweight alternative, making them suitable for structural applications requiring moderate delamination resistance, such as automotive body panels, aerospace interior structures, and impact-resistant components [25, 26]. Fig. 8 shows the interlaminar shear strength results, highlighting Sample 3 (GJJG) as the best performer due to optimized fiber stacking and ESNP reinforcement, which enhance delamination resistance and stress transfer efficiency for high-performance applications.

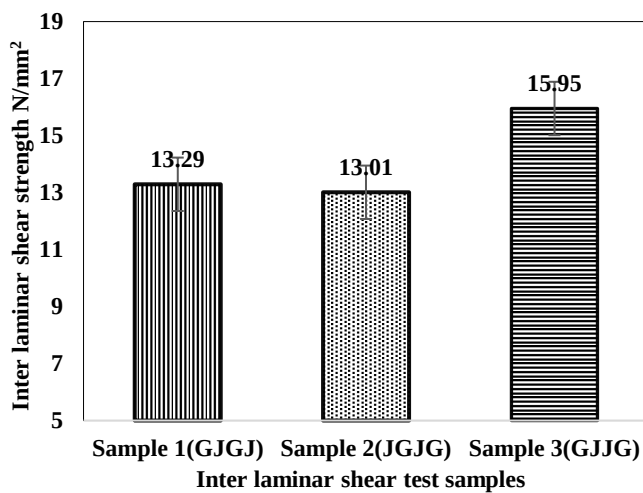


Fig. 8. Interlaminar shear strength of hybrid composite

4.4. Impact strength

The impact resistance of the hybrid composites was evaluated to determine their ability to absorb energy under sudden loading conditions, which is crucial for applications in automotive crashworthiness, aerospace components, and protective structures. The results indicate that Sample 3 (GJJG) exhibited the highest impact strength of 4.6 J, followed by Sample 1

(GJGJ) at 4.2 J and Sample 2 (JGJG) at 3.9 J. The superior impact resistance of Sample 3 is attributed to its optimized fiber stacking sequence, which enhances stress redistribution and energy dissipation during impact loading. The contribution of eggshell nanoparticles (ESNPs), a control sample without nanoparticles, was tested. It recorded an impact strength of 3.1 J, which is 22–32 % lower than the ESNP-reinforced composites. Incorporating 10 % ESNPs facilitated crack deflection, reduced micro-crack propagation, and improved interfacial bonding, thereby increasing fracture toughness and energy absorption capacity [27]. These results are consistent with previous studies, demonstrating that CaCO₃-based nanofillers enhance polymer composites by impeding crack growth and reinforcing stress transfer mechanisms.

Scanning Electron Microscopy (SEM) analysis of Sample 3's impact fracture surface reveals well-embedded fibers, reduced matrix voids, and uniform ESNP dispersion, contributing to its enhanced toughness. In contrast, Sample 1 and Sample 2 exhibited fiber pull-out and microstructural inconsistencies, which diminished their ability to resist impact-induced damage. The findings confirm that nanoparticle reinforcement and fiber architecture improve impact resistance by increasing crack-arresting mechanisms, energy dissipation efficiency, and matrix ductility [28, 29]. Fig. 9 shows the impact strength of hybrid composites, with Sample 3 (GJJG) exhibiting the highest value due to superior fiber-matrix bonding and uniform ESNP dispersion.

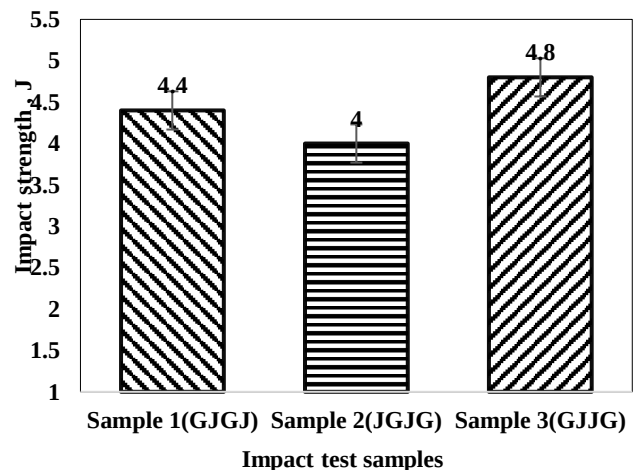


Fig. 9. Impact strength of hybrid composites

Improved adhesion reduced fiber pull-out and micro-crack propagation, enhancing energy absorption. Samples 1 (GJGJ) and 2 (JGJG) showed lower impact resistance due to increased delamination and voids.

4.5. Microstructural analysis

The microstructural analysis of the hybrid composites, conducted using Scanning Electron Microscopy (SEM,

Zeiss EVO 18), revealed significant differences in fiber-matrix adhesion, nanoparticle dispersion, and failure mechanisms across the samples. The Scanning Electron Microscopy (SEM) analysis (Fig. 4 and Fig. 6) provided critical insights into the dispersion of eggshell nanoparticles (ESNPs), fiber-matrix adhesion, and failure mechanisms in the fabricated hybrid composites. Fig. 4, illustrating the tensile fracture of Sample 3 (GJJG), revealed well-integrated fiber-matrix bonding with minimal fiber pull-out and uniform ESNP distribution, contributing to enhanced stress transfer and reduced micro-crack propagation. Similarly, Fig. 6, showing the flexural fracture of Sample 3, demonstrated strong interfacial adhesion and limited delamination, confirming the role of ESNPs in reinforcing the composite structure. In contrast, Samples 1 (GJJG) and 2 (JJGG) exhibited localized nanoparticle agglomeration and increased void content, leading to weaker mechanical performance and susceptibility to early failure. The control sample (without ESNPs) further validated the reinforcing effect of nanoparticles, as it displayed higher void formation, weaker fiber-matrix adhesion, and reduced fracture resistance.

Compared to previously studied non-nanoparticle-reinforced composites (with tensile strengths around 55–60 MPa), the ESNP-reinforced samples demonstrated a 15–30 % improvement, highlighting nano-fillers' effectiveness in strengthening hybrid composites. These observations align with interlaminar shear strength (ILSS) results, confirming that fiber stacking order and nanoparticle dispersion significantly influence delamination resistance and mechanical durability. The SEM images affirmed the nano-scale structure (50–100 nm) of ESNPs, their uniform integration in optimized stacking configurations, and their contribution to developing lightweight, high-strength, and structurally resilient hybrid composites [30, 31].

5. CONCLUSIONS

This study successfully developed and characterized nano-enhanced hybrid composites by integrating woven jute fabric, E-glass fibers, and eggshell nanoparticles (ESNPs) in an epoxy matrix. The incorporation of 10% ESNPs significantly improved mechanical properties, with Sample 3 (GJJG) demonstrating the highest tensile strength (77.77 MPa), flexural strength (452.72 MPa), impact strength (4.8 J), and interlaminar shear strength (15.95 N/mm²), representing increases of 24.7 %, 16.5 %, 6.7 %, and 20 %, respectively, compared to the lowest-performing sample. A key insight from this study is that hybridization with ESNPs bridges the performance gap between natural and synthetic fiber composites, enhancing interlaminar shear strength, flexural behavior, and impact resistance while maintaining a lighter and more sustainable structure. SEM analysis confirmed uniform ESNP dispersion, reduced microvoids, and improved fiber-matrix bonding, improving stress transfer efficiency and crack resistance. Although pure glass fiber composites typically exhibit flexural strengths of 500–600 MPa and ILSS values of 18–22 N/mm², the ESNP-reinforced hybrid composites showed a 15–30 % reduction in these properties due to the lower stiffness of jute fibers. However, the mechanical

performance and sustainability trade-offs make these composites a viable lightweight alternative for semi-structural applications, such as automotive crash-resistant panels, aerospace components, and energy-absorbing structures. Future research should focus on long-term durability studies, optimizing ESNP concentration, and assessing environmental degradation effects to further improve their industrial viability and sustainability.

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