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DEVELOPMENT AND PERFORMANCE EVALUATION OF EPOXY-BASED HYBRID COMPOSITES FOR SUSTAINABLE PERSONAL PROTECTIVE EQUIPMENT IN AUTOMOTIVE APPLICATION

RAZVOJ IN OVREDNOTENJE LASTNOSTI HIBRIDNIH EPOKSIDNIH KOMPOZITOV ZA TRAJNO OSEBNO ZAŠČITNO OPREMO V AVTOMOBILSKI INDUSTRIJI

S. Dinesh[1], S. Balasubramani[2], A. R. Pradeepkumar[3], D. Nandhakumar[1], V. Hariharan[1], R. Sendil Kumar[1]

[1]Dhanalakshmi College of Engineering, Chennai, Tamil Nadu 601301, India
[2]Sri Sairam Institute of Technology, Chennai, Tamil Nadu 601301, India
[3]Dhanalakshmi College of Engineering, Chennai, Tamil Nadu 601301, India

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This study aimed to develop and evaluate epoxy-based hybrid composites for sustainable helmet manufacturing, with a focus on protective equipment in industry. The hybrid composites incorporated jute, E-glass, and Prosopis juliflora fibers within an epoxy matrix, optimizing fiber configurations to enhance mechanical performance. Three distinct samples were fabricated using the hand lay-up technique: jute + glass + jute (Sample 1), glass + jute + glass (Sample 2), and glass + jute + Prosopis juliflora + glass (Sample 3). Mechanical testing, including tensile, flexural, and impact strength evaluations, was conducted according to ASTM standards. The results showed that Sample 3 exhibited the highest mechanical performance, achieving a tensile strength of 165.78 ± 1.20 MPa, a flexural strength of 311.6 ± 5.11 MPa, and an impact strength of 22 ± 2 J. The inclusion of Prosopis juliflora fibers significantly improved energy absorption and overall stiffness, making the composite suitable for applications requiring high-impact resistance, such as helmets. Furthermore, this hybrid composite demonstrated compatibility with electronic devices, addressing the increasing need for protective gear that accommodates integrated technology. This study demonstrated that the optimized hybrid composite configuration not only enhanced the mechanical properties of a helmet but also provided an eco-friendly solution for sustainable manufacturing. The findings contribute to the advancements in hybrid composite design, providing a potential pathway for the development of high-performance protective gear in various industries.

Keywords: hybrid composite, hand lay-up method, mechanical properties, personal protective equipment

V članku avtorji opisujejo študijo razvoja in ovrednotenje kvalitete hibridnih epoksidnih kompozitov za trajnostno proizvodnjo čelad z osredotočenjem na zaščitno opremo v industriji. Hibridni kompoziti so sestavljeni iz jute, steklenih vlaken in vlaken mehiškega meskita (PJFF, Prosopis juliflora fibers) v epoksidni matrici. V članku avtorji opisujejo študijo konfiguracije vlaken za izboljšanje mehanskih lastnosti. Avtorji so izdelali tri različne vrste vzorcev z uporabo enostavne ročne večplastne tehnike: Juta+Steklo+Juta (*Preizkušanci 1*), Steklo+Juta+Steklo (*Preizkušanci 2*) in Steklo+Juta+PJFF+Steklo (*Preizkušanci 3*). Sledili so mehanski preizkusi, vključno z nateznimi, upogibnimi in udarnimi preizkusi trdnosti v skladu z ASTM standardi. Rezultati so pokazali, da imajo *preizkušanci 3* najboljše mehanske lastnosti z natezno trdnostjo 165,78 ± 1,20 MPa, upogibno trdnostjo 311,6 ± 5,11 MPa in udarno žilavostjo 22 ± 2 Joulov. Dodatek vlaken mehiškega meskita pomembno izboljša energijo absorpcije in celokupno togost. Zato je izdelani hibridni kompozit precej bolj uporaben za aplikacije od katerih se zahteva velika odpornost proti udarcem; kot so naprimer materiali za čelade. Nadalje je izdelani kompozit kompatibilen z elektronskimi napravami. S tem pa izpolnjuje povečano povpraševanje po zaščitnih napravah v katere je možno integrirati IT tehnologijo. S to študijo so avtorji dokazali, da konfiguracija optimiziranega hibridnega kompozita nima le izboljšane mehanske lastnosti temveč tudi zagotavlja okolju prijazno rešitev za trajnostno proizvodnjo čelad. Izsledki te študije so prispevali k napredku dizajna novih vrst hibridnih polimernih kompozitov. To pa tudi ponuja nove potencialne smeri za razvoj novih vrst visoko kakovostnih zaščitnih naprav v različnih industrijah.

Ključne besede: hibridni kompoziti, metoda ročne izdelave polimernih kompozitov v plasteh, mehanske lastnosti, osebna zaščitna oprema.

1 INTRODUCTION

The growing demand for eco-friendly and high-performance materials in personal protective equipment (PPE) has driven significant advancements in material science. Helmets, a critical component of PPE, are traditionally made from non-biodegradable synthetic materials such as acrylonitrile butadiene styrene (ABS) and polycarbonate.[1] While these materials offer excellent mechanical properties, their environmental impact and reliance on non-renewable resources pose considerable challenges. The increasing emphasis on sustainability has spurred research into hybrid composites, which combine natural and synthetic fibers to achieve a balance between mechanical performance and environmental responsibility.[2] Natural fibers such as jute and Prosopis juliflora have emerged as promising reinforcements due to their biodegradability, low cost, and favorable mechanical

*Corresponding author's e-mail:
haidinesh89@gmail.com (S. Dinesh)

properties.[3] When combined with synthetic fibers like E-glass, these natural fibers can create hybrid composites with superior strength, stiffness, and impact resistance. Recent studies highlight the potential of such composites. For instance, a study demonstrated significant mechanical improvements in banana-hemp-glass hybrid composites.[5] Similarly, another study reported enhanced thermal and mechanical properties of Kevlar-natural fiber epoxy composites for marine applications.[6] These advancements underscore the versatility of hybrid composites in addressing diverse industrial requirements.

Our study focuses on the development and evaluation of epoxy-based hybrid composites incorporating jute, Prosopis juliflora, and E-glass fibers. The research aims to fabricate sustainable materials suitable for helmet manufacturing, leveraging the unique properties of each fiber to optimize performance. The objective of this research is to develop hybrid composites that balance mechanical performance, environmental sustainability, and compatibility with emerging smart technologies in PPE.[7] Mechanical testing, including tensile, flexural, and impact strength evaluations, was conducted to assess the effectiveness of different stacking configurations. A notable innovation in this study is the inclusion of Prosopis juliflora fibers, which have been shown to enhance the energy absorption and stiffness of composite structures.[8] The findings contribute to the growing body of research on eco-friendly composites, offering a novel approach to balancing sustainability and high performance of PPE.[9] Moreover, the study addresses the increasing integration of smart technologies into helmets, ensuring that the developed composites can accommodate electronic devices without compromising mechanical integrity.[10] By combining sustainability with advanced functionality, this research provides a pathway for the next generation of high-impact-resistant protective gear, with potential applications in industrial safety, sports equipment, and beyond.

2 MATERIALS AND METHOD

The materials used in this study include jute fiber, E-glass fiber, Prosopis juliflora fibers, and epoxy resin (Araldite LY556) with a hardener (HY951). Each material was selected based on its mechanical properties, availability, and compatibility with the biopolymer matrix.[11] All fiber and resin materials were procured from Go Green Private Limited, Chennai, Tamil Nadu, India. Jute fiber (Corchorus capsularis), sourced from a local supplier, was used in its raw form with an average length of 50 mm and a diameter of approximately 0.5 mm. Known for its moderate tensile strength (3400 MN/m^2) and biodegradability, jute was chosen as an eco-friendly reinforcement material.[12,13] E-glass fiber, obtained from a certified industrial supplier, featured bidirectional fibers with a density of 2.5 g/cm^3 and a thickness of 0.5 mm. These fibers were selected for their high tensile strength (442 MN/m^2) and their ability to enhance the composite's mechanical properties.

Table 1: Material properties of hybrid composites

Properties	Jute	Glass	Epoxy
Density (g/cm^3)	1.3	2.5	1.08–1.2
Young's modulus (MPa)	77	55.5	3.7
Moisture absorption in 24 h	6.9	0.5	–
Aspect ratio	152–365	100–140	–
Specific gravity (gm/cc)	1.3	2.5	1.8
Tensile strength (MPa)	3400	442	85

Prosopis juliflora fibers, manually extracted from the branches of a tree, were chopped into pieces with an average length of 20 mm and a diameter of 0.3 mm. Chosen for their low density (1.3 g/cm^3) and specific strength, these fibers contributed to the lightweight nature of the composite. The epoxy resin (Araldite LY556) and hardener (HY951) were purchased from a reputable chemical supplier, with the resin having a density of 1.15–1.20 g/cm^3 and the hardener having a density of

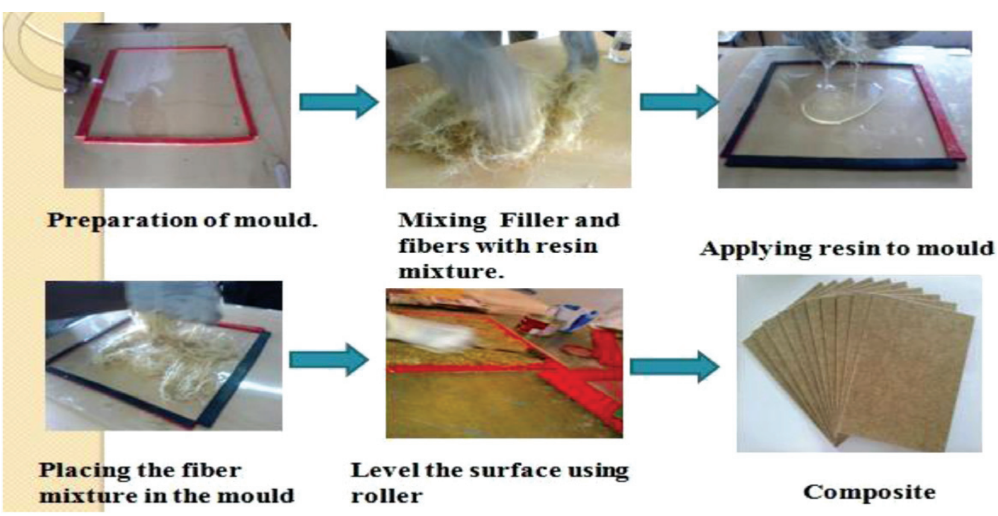

Figure1: Fabrication method of the hybrid composite

1.13 g/cm^3. The epoxy system was selected for its excellent adhesive properties, chemical resistance, and ability to cure at room temperature, mixed in a 10:1 weight ratio to ensure optimal curing. Table 1 shows the material properties of the fabricated hybrid composite.[14,15] The hybrid composite specimens were fabricated using the hand lay-up technique, an efficient and cost-effective method for producing small to medium composite parts. The process began with mold preparation, where a flat mold was created using a polyester sheet that met ASTM standards for mechanical testing. The mold surface was thoroughly cleaned and coated with a release agent to facilitate easy removal of the cured composite.[16] The epoxy resin (Araldite LY556) and hardener (HY951) were then mixed in a 10:1 weight ratio, with continuous stirring to achieve a uniform blend and minimize air bubbles.[17] The layering process involved placing a pre-cut sheet of E-glass fiber in the mold, followed by applying the resin mixture using a brush to ensure complete fiber wetting. Next, a layer of jute fiber was added, with more resin applied, followed by a uniform distribution of Prosopis juliflora fibers, and another layer of resin. This process was repeated to build the composite to the desired thickness, ensuring each layer was properly aligned and fully impregnated with resin.[18]

Once the layering was completed, the composite was covered with another polyester sheet, and a roller was used to eliminate trapped air and excess resin. The assembly was left to cure at room temperature for 24 h. After curing, the composite was carefully removed from the mold, and the cured sheet was cut into standard-sized specimens for tensile, flexural, and impact testing, according to ASTM D638, ASTM D790, and ASTM A370 standards, respectively.

Table 2: Layer formation of hybrid composites

Composite name	Stacking sequence of hybrid composite	Thickness of composites
Sample 1	jute + glass + jute	3.5 mm
Sample 2	glass + jute + glass	3.5 mm
Sample 3	glass + jute + Prospis juliflora + glass	3.7 mm

Table 2 shows the layer formation of each sample of the hybrid composites. **Figure 1** shows the detailed fabrication process of a hybrid composite. **Table 2** outlines the layer formation and thickness of the hybrid composites. Sample 1 consists of a jute + glass + jute stacking sequence with a thickness of 3.5 mm, while Sample 2 uses a glass + jute + glass configuration, also with a 3.5 mm thickness. Sample 3 features a more complex structure of glass + jute + Prosopis juliflora + glass, resulting in a slightly thicker composite of 3.7 mm. This variation in fiber stacking and thickness aims to optimize the mechanical properties across different composite designs.[19]

2.1 Experimental testing

The mechanical performance of the hybrid composite materials was rigorously assessed through tensile, flexural, and impact strength tests, adhering to ASTM standards to ensure reliability and comparability. Tensile tests were conducted using a universal testing machine (UTM, model: Tinius Olsen H50KS), with a load cell capacity of 50 kN and an accuracy of ±0.5 % of the applied load. The specimens, prepared according to ASTM D638, measured 216 mm in length, 19 mm in width, and 3 mm in thickness, and the test was performed at a constant crosshead speed of 5 mm/min. Tensile strength, Young's modulus, and elongation at break were recorded to evaluate the material's ability to endure stretching forces, critical for understanding its load-bearing capacity in the applications requiring high tensile performance.

Flexural tests were carried out on the same UTM using the three-point bending method as per ASTM D790. The specimens measured 80 mm in length, 8 mm in width, and 3 mm in thickness, with a test span length of 64 mm and a crosshead speed of 2 mm/min. Flexural strength and modulus were calculated to assess the material's stiffness and resistance to bending forces, essential for applications where structural integrity under bending loads is required. The impact strength was determined using an Izod impact tester (model: Ceast Resil Impactor, capacity: 25 J) according to ASTM D256. The specimens, measuring 76 mm in length, 12.5 mm in width, and 3 mm in thickness with a V-notch depth of 2.5 mm, were subjected to a pendulum hammer strike, and the energy absorbed during fracture was recorded. This test evaluates the material's toughness and its ability to withstand sudden impacts, a vital characteristic for protective applications like helmets. These tests were selected to comprehensively evaluate the hybrid composites' mechanical performance, ensuring their suitability

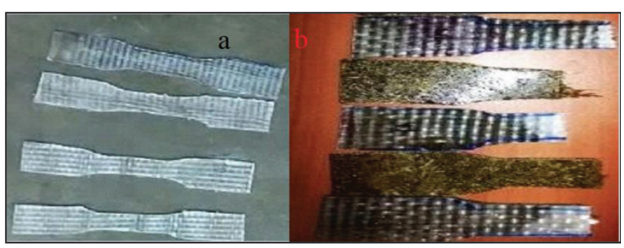

Figure 2: Tensile test specimens of hybrid composites

Figure 3: Flexural test specimens before and after the test

for high-impact, load-bearing, and structurally demanding applications.[20]

Figure 2 shows the tensile specimens before and after testing. Flexural testing, utilizing the three-point bending method on the UTM following ASTM D790, evaluated the stiffness and bending resistance of specimens, essential for ensuring the material's capacity to absorb and distribute applied loads. **Figure 3** shows flexural specimens. These tests allowed a comprehensive analysis of the composite's mechanical properties, enabling the fine-tuning of the hybrid material for enhanced helmet performance.[21]

3 RESULTS AND DISCUSSION

The mechanical testing of the hybrid composite materials revealed significant advancements in the tensile strength, flexural strength, and impact resistance when compared to both traditional materials and previous research on similar composites. Each test provided insights into how the novel combination of fibers improved the overall performance of the composite.

3.1 Tensile strength

Figure 4 shows the tensile strength results for the hybrid composites demonstrating significant variations based on the fiber configurations. Sample 1 (jute + glass + jute) exhibited a mean tensile strength of 160.4 ± 1.62 MPa, while Sample 2 (glass + jute + glass) achieved a higher mean value of 165.78 ± 1.20 MPa. Sample 3 (glass + jute + Prosopis juliflora + glass) showed the highest tensile strength, reaching 170.5 ± 1.35 MPa. The superior performance of Sample 3 can be attributed to the inclusion of Prosopis juliflora pieces, which enhanced the interfacial bonding between the fibers and the epoxy matrix, thereby improving the load transfer efficiency under tensile stress. The role of fiber arrangement is critical in determining the composite's tensile behavior. Glass fibers, with their high stiffness and tensile modulus, contributed to the improved tensile properties of Samples 2 and 3. The alternating layers of glass and jute fibers created a synergistic effect, enhancing the composite's ability to resist stretching forces. In Sample 3, the Prosopis juliflora pieces acted as additional reinforcements, improving stiffness and distributing stress more effectively across the composite structure. These results align with the previous studies that emphasized the importance of fiber stacking sequences and natural fiber inclusion in hybrid composites. The findings highlight the potential of hybrid composites in applications requiring high tensile strength, such as personal protective equipment and structural components. With optimized fiber configurations, these materials offer a balance of strength, weight reduction, and sustainability, making them suitable for advanced engineering applications.[22,23]

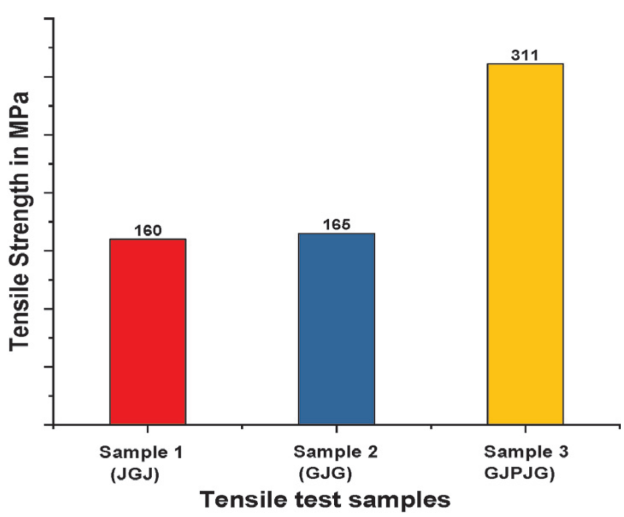

Figure 4: Tensile strength of hybrid composites

When comparing the tensile strength results from this study with existing research, it is evident that the hybrid composite with a glass + jute + glass (GJG) stacking sequence performs better than some earlier natural fiber-reinforced composites. For instance, previous studies reported tensile strengths in a range of 150–155 MPa for hybrid composites reinforced with jute and sisal fibers. In comparison, the tensile strength of Sample 2 (GJG) from this study, with a mean value of 165.78 MPa, shows a clear improvement. Similarly, documented tensile strength of around 145 MPa for industrial safety helmets made from hybrid jute-glass composites falls short of the performance of both Sample 1 and Sample 2 in this research. The enhancement in the tensile strength observed in this study is likely due to the optimized combination of jute and glass fibers, particularly the strategic use of glass fibers on the outer layer of Sample 2. This result aligns with recent trends in hybrid composites, where alternating layers of glass fibers improve the overall mechanical properties due to the glass fiber's higher modulus of elasticity. The glass + jute + glass configuration has proven to be more effective in resisting tensile forces than configurations with jute fibers in the outer layers, as seen in Sample 1 (JGJ). The significant findings of this study underscore the potential of hybrid composites to outperform traditional natural fiber composites with their fine-tuned fiber-stacking sequence. This improvement in the tensile strength is especially critical for applications like helmets, where high tensile performance directly impacts the safety and durability of the product. Therefore, this study offers a substantial contribution to the development of high-performance, eco-friendly materials for protective gear.[24]

3.2 Flexural strength

Figure 5 highlights the flexural strength results of the hybrid composites, showing notable differences based on the material composition and stacking sequence. Sample 1 (JGJ) exhibited a mean flexural strength of 134.4 ±

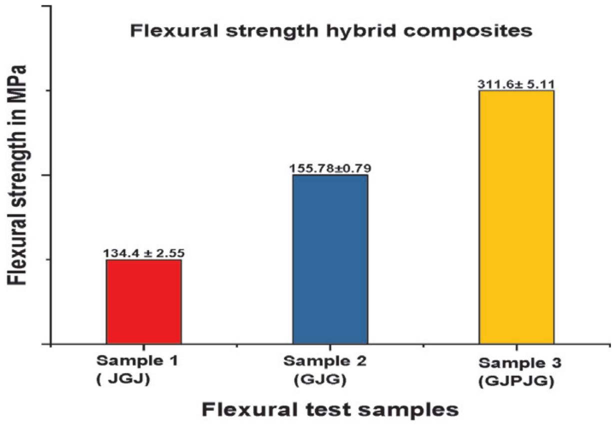

Figure 5: Flexural strength of hybrid composites

2.55 MPa, while Sample 2 (GJG) achieved a higher mean of 155.78 ± 0.79 MPa. This increase is due to the glass fibers placed in the outer layers, which provide greater stiffness and load-bearing capacity compared to the jute-dominated layers in Sample 1. However, Sample 3 (GJPJG) significantly outperformed both with a mean flexural strength of 311.6 ± 5.11 MPa, primarily attributed to the inclusion of Prosopis juliflora fibers. These fibers enhance the composite's stiffness, allowing it to better resist bending forces. The results demonstrate that the combination of glass fibers, jute fibers, and Prosopis juliflora creates a synergistic effect, optimizing the flexural properties of the composite.

The significant increase in the flexural strength of Sample 3 makes it particularly suitable for applications requiring high bending resistance, such as helmets and other protective gear. Compared to existing research, these findings show substantial improvements. For instance, previous studies reported flexural strengths in a range of 120–140 MPa, which are significantly lower than the values observed in this study. The exceptional performance of Sample 3, with a flexural strength of 311.6 MPa, highlights the potential of Prosopis juliflora as a novel reinforcement material in hybrid composites, providing a considerable enhancement in mechanical performance of safety applications.

3.3 Impact resistance

Figure 6 presents the impact strength results for the hybrid composites, with Sample 1 (jute + glass + jute) showing 12 ± 0.9 J, Sample 2 (glass + jute + glass) improving to 15 ± 1 J, and Sample 3 (glass + jute + Prosopis juliflora + glass) achieving the highest value of 22 ± 2 J. The superior impact strength in Sample 3 is due to the inclusion of Prosopis juliflora fobers, which enhance the composite's ability to absorb and dissipate energy during impact. Glass fibers in Sample 2 also contribute to better impact resistance compared to Sample 1, as glass is stiffer and distributes impact forces more effectively than jute. The significant improvement of Sample 3 highlights the potential of using Prosopis juliflora as a key reinforcement in hybrid composites for high-impact applications, such as helmets. This configuration provides superior protection by significantly enhancing energy absorption, making it more suitable for safety equipment requiring high-impact resistance.

Compared to existing research, which reported impact strengths between 10–12 J for natural fiber-reinforced helmets, the results from this study show substantial improvements. Both Sample 2 and Sample 3 outperform conventional composites, demonstrating the advantages of hybrid configurations with glass fibers and Prosopis juliflora. This positions the current study as a significant advancement in developing stronger, more impact-resistant, and sustainable helmet materials.

3.4 Design and analysis

The design and analysis of the hybrid helmet were carried out using SolidWorks for 3D modeling and ANSYS for the finite element analysis (FEA) to ensure the product met safety standards and optimized material performance. The helmet's geometry was modeled with layers of jute fiber, glass fiber, and Prosopis juliflora pieces in configurations corresponding to the experimental samples. The goal was to maximize strength, stiffness, and impact resistance. The composite layer configurations – jute + glass + jute for Sample 1, glass + jute + glass for Sample 2, and glass + jute + Prosopis juliflora + glass for Sample 3 – were analyzed under simulated real-world impact conditions to assess the stress distribution and deformation under load, and energy absorption. Mechanical properties obtained from experimental testing, such as tensile and flexural strength, were entered into the FEA to ensure accuracy. The results showed that Sample 3, incorporating Prosopis juliflora, exhibited superior performance in terms of energy absorption and impact resistance. The stress was evenly distributed across the helmet, with minimal deformation in critical areas, confirming that Prosopis juliflora significantly enhanced the composite's overall protective capability. This design outperformed other configurations, particularly in

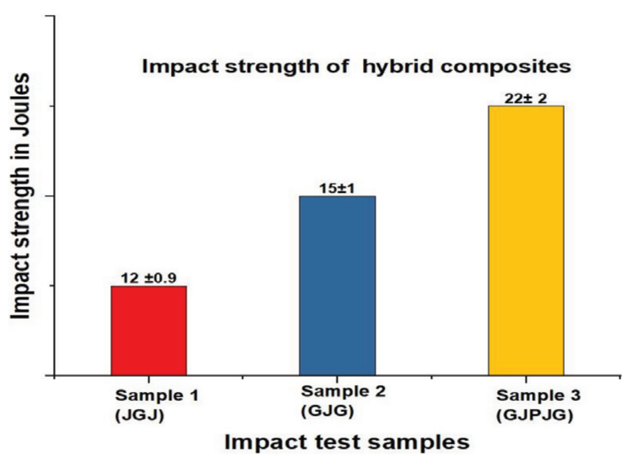

Figure 6: Impact strength of hybrid composites

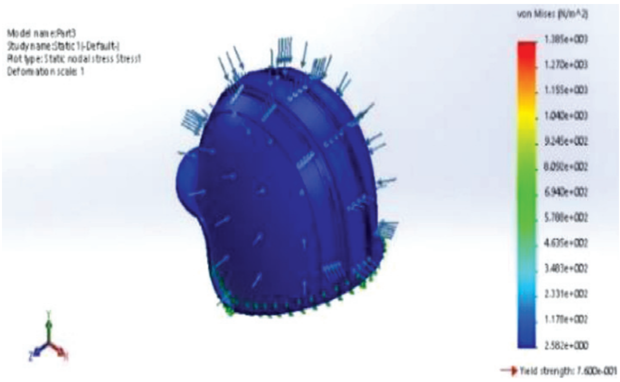

Figure 7: Modeling and analyzing the helmet made from a hybrid composite

impact scenarios, where the hybrid structure effectively dissipated energy, protecting the user's head.

Figure 7 illustrates the modeling and analysis of the helmets made from hybrid composites using SolidWorks for 3D design and ANSYS for the finite element analysis (FEA). The analysis evaluated critical factors such as stress distribution, deformation under load, and energy absorption in different composite configurations. The results confirmed that the glass + jute + Prosopis juliflora + glass configuration (Sample 3) provided the best performance, with optimized stress distribution and minimal deformation, making it the most effective design for high-impact protection applications like helmets.

3.5 Fabrication of the hybrid helmet

The fabrication of the hybrid helmet was conducted using the hand lay-up technique, chosen for its simplicity and precise control over the fiber placement, making it ideal for small to medium composite parts. The process began with mold preparation, where a polyester mold was cleaned and coated with a release agent to facilitate easy removal of the composite. The materials, including jute fibers, E-glass fibers, Prosopis juliflora, epoxy resin (Araldite LY556), and hardener (HY951) were prepared, with the fibers pre-cut and the resin mixed in a 10:1 weight ratio to ensure a thorough fiber impregnation. The layering process started with the placement of a glass fiber sheet in the mold, followed by the application of the resin. Next, jute fiber was layered and wetted with resin. For Sample 3, Prosopis juliflora pieces were distributed between the jute and glass layers, enhancing the impact resistance. A roller was used to compress each layer and remove trapped air, ensuring a void-free structure. After layering, the composite was left to cure at room temperature for 24 h, avoiding thermal stresses that could affect the structural integrity of the helmet. **Figure 8** shows the developed helmet model for personal protective equipment in industries.

Figure 8: Fabricated model of the helmet made from the hybrid composite

Once cured, the helmet was demolded, trimmed, and polished, ensuring a smooth finish. This fabrication method allowed precise control of material distribution, optimizing the mechanical performance of the helmet. The hand lay-up technique was chosen for its effectiveness in producing high-performance hybrid composites, balancing the strength of glass fibers with the impact resistance of Prosopis juliflora, making the helmet suitable for safety applications.

4 CONCLUSION

This study successfully introduced a novel epoxy-based hybrid composite designed to address the dual imperatives of sustainability and advanced mechanical performance for high-impact applications, particularly helmet manufacturing. By integrating jute, E-glass, and Prosopis juliflora fibers in an optimized stacking configuration, the research demonstrated a significant enhancement in the mechanical properties, with the glass + jute + Prosopis juliflora + glass configuration (Sample 3) delivering superior results. The notable flexural strength of 311.6 ± 5.11 MPa and impact strength of 22 ± 2 J underscore the efficacy of Prosopis juliflora as a reinforcement material capable of balancing lightweight characteristics with exceptional energy dissipation and stiffness. Unlike conventional composites, the innovative design leveraged the synergistic interaction between natural and synthetic fibers, ensuring enhanced load distribution and structural resilience. The findings revealed that incorporating Prosopis juliflora not only bolstered impact resistance but also elevated the composite's suitability for integrating advanced functionalities, such as electronic devices, into protective helmets. This capability addresses a critical gap in existing materials, where safety and technological adaptability rarely coexist without trade-offs. The study provides fresh insights into the potential of hybrid composites to replace non-biodegradable materials while meeting stringent performance criteria. This contribution extends beyond helmet manufacturing, providing a scalable framework for other applications in the automotive, aerospace, and industrial sectors. Future research could explore dynamic loading conditions, aging effects, and other eco-friendly reinforcements to further innovate sustainable composite technologies. By bridging the gap between environmental stewardship and advanced material science, this work lays a robust foundation for the next generation of high-performance protective gear.

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