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Characterization and Analysis of Mechanical and Morphological Properties of Hybrid Composite Material from Prosopis Juliflora and Phoenix Sylvestris for Engineering Applications

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The demand for sustainable, high-performance materials has driven interest in natural fiber-based composites. This research investigates the development of a hybrid composite using fibers from Prosopis Juliflora and Phoenix Sylvestris combined with glass fibers and epoxy resin. The natural fibers underwent a 10% NaOH treatment to enhance their mechanical properties. Hand layup techniques were employed to fabricate the samples, followed by comprehensive mechanical testing, including tensile, flexural, impact, hardness, and delamination tests. The composite, composed of 60% natural fibers, and 30% resin, and treated with NaOH, exhibited superior mechanical performance, surpassing similar composites in literature. Scanning electron microscopy (SEM) analysis revealed improved fiber-matrix adhesion, while wear testing indicated potential applications in brake linings. The results suggest this hybrid composite offers a viable, sustainable alternative for high-performance engineering applications, particularly in the automotive industry.

Keywords: biocomposite, hand lay-up technique, mechanical test, engineering application.

1. INTRODUCTION

Prosopis juliflora represents a significant environmental and socio-economic challenge in many regions where it has become invasive, necessitating concerted efforts for its management and control to mitigate its adverse impacts [1, 2]. The Prosopis juliflora fiber-reinforced composite has higher shear strength after alkaline treatment. The density of fiber (0.58 g/cm3) is less than the synthetic composite. Prosopis juliflora fiber has higher mechanical properties than synthetic fibers and is biodegradable. Hybrid composites of Prosopis juliflora (PJ) and rice husk, reinforced with epoxy resin, were fabricated with filler ratios up to 20 % using compression molding. Mechanical properties were evaluated to understand rice husk's influence and identify optimal configurations for improved performance. Results offer insights into enhancing mechanical strength through uniform dispersion, contributing to sustainable composite material development [3]. Prosopis juliflora fiber composites were made using hand layup, incorporating 0 – 16 wt.% barium sulfate filler. Mechanical testing indicated optimal performance at 12 wt.% filler, as higher filler content reduced tensile and flexural strength, while impact strength remained consistent [4]. SEM analysis revealed an even distribution of barium sulfate, enhancing mechanical properties. Natural fibers, including Banana fiber, Prosopis juliflora fiber, and Coconut fiber, were utilized to reinforce epoxy composites with varying weight percentages through hand layup. Mechanical tests revealed significant improvements in tensile and flexural strength, with alkali-treated specimen F showing the highest values [5]. Additionally, alkali treatment enhanced impact and hardness properties. Morphological analysis demonstrated uniform fiber mixing and improved interfacial interaction, enhancing overall mechanical attributes [6]. These bio-composites hold potential for diverse applications including packaging, automotive parts, shipping, and construction industries. GFRP with 6 % Prosopis Juliflora outperforms standard GFRP due to secondary reinforcement improved interfacial bonding and excellent chemical resistance [7]. Researchers have noted challenges in employing natural fibers in polymer composites, including uneven stress distribution and inadequate interfacial adhesion, which may impair load transfer efficiency and mechanical performance [8, 9]. Additionally, the hydrophilic nature of natural fibers leads to water absorption, causing swelling within the composite matrix and potentially weakening the interfacial bonding over time. Consequently, the tribomechanical performance of the composite may gradually deteriorate during use. To address these difficulties, strategies such as surface modification of fibers, incorporation of coupling agents, and optimization of processing techniques are employed to enhance interfacial adhesion and minimize water absorption, thereby improving the overall performance of composites. The research aims to hybridize Prosopis juliflora fiber, Phoenix Sylvestre, and glass fiber reinforced with an epoxy resin matrix. Fabricating composite has higher mechanical properties and is enhanced for automotive applications.

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2. MATERIALS AND METHOD

The direct fibers extraction from Prosopis juliflora bark and Phoenix sylvestre leaf stems, the materials were immersed in water for 24 hours. After soaking, the fibers were carefully extracted using a knife and the water retting method, ensuring efficient separation of the fibers from the bark of Prosopis juliflora and the leaf stems of Phoenix Sylvestre. Yielding fibers with dimensions ranging from 0.2 to 1.2 mm in thickness, approximately 30 cm in length, and a density of 0.5 g/cm^3, with an average length of 25 cm for Prosopis juliflora fibers. In the composite fabrication, E-glass fiber was used, typically with a diameter ranging from 10 to 15 micrometers, which is ideal for its high strength and good insulation properties. Depending on the application, either continuous strands or chopped fibers were utilized, with the latter usually measuring around 3 to 25 mm in length. The glass fiber offers a tensile strength of approximately 3400 MPa and a Young's Modulus of about 70 – 85 GPa, contributing to the composite's overall mechanical properties. These fibers are subsequently immersed in a 10 % NaOH (sodium hydroxide) solution, mixed with water, to eliminate impurities and enhance their properties. After soaking of fiber, dry at room temperature for 3 hours. Simultaneously, glass woven fabric fiber, epoxy resin (Ly 556), hardener (HY951), and silicon spray are sourced from Herbana Pvt. Ltd in Chennai, India. These materials likely serve as additional components for integration with the treated fibers in a composite fabrication process, aimed at achieving specific material characteristics [9, 10].

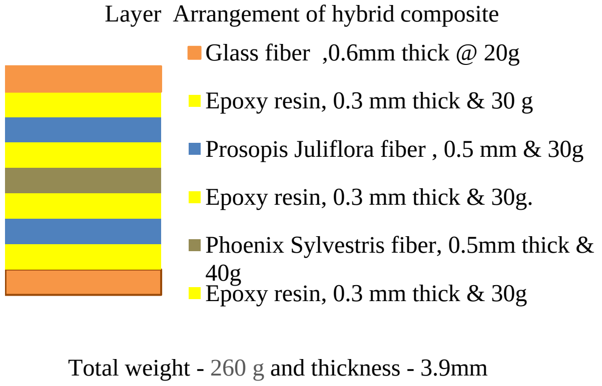

Fig. 1. Layer formation of hybrid composite

The fabrication process utilizes a hand lay-up with a compressed molding technique on a plain flat surface for composite fabrication, preceded by spraying the surface with silicon spray as a relieving agent. Glass woven fabrics are employed for both the bottom and top layers, while Prosopis juliflora fiber is positioned as the second and top layers, with Phoenix sylvestre fiber acting as the intermediate layer. Between the fiber layers, a coating of resin (epoxy resin and hardener), stirred in a 1:10 ratio (10 ml hardener and 100 ml epoxy resin), is applied, with stirring at 50 rpm at atmospheric temperature [11]. Following layer formation, a consistent resin distribution is applied over the composite. After a two-day later, the load is removed, and the fabricated composite undergoes thorough drying. Subsequently, the sample is cut into specimens according to ASTM standards for further property evaluation [12, 13]. Fig. 1 shows the layer formation of the current hybrid composite. The hybrid composite has a thickness of 3.9 mm and a weight of 269 grams.

3. EXPERIMENTAL TESTING

The experimentation involved utilizing a UTM 300 testing machine to conduct various tests following ASTM standards. Tensile strength tests (ASTM D638), and flexural tests (ASTM D 790) were performed, along with impact tests using the Izod test method (ASTM D 276). Hardness was measured according to ASTM D2583, and delamination tests were conducted following ASTM 5528 standard procedures. Additionally, microstructural was evaluated by scanning electron microscopy, and water resistance behavior was assessed following ASTM D570 Standard. Each test utilized five specimens, and the average values were evaluated for analysis.

4. RESULTS AND DISCUSSION

4.1. Tensile strength

The tensile strength results of the Prosopis Juliflora and Phoenix Sylvestris hybrid composite exhibit outstanding mechanical properties, with a tensile strength of 155.6 ± 4.4 MPa and a tensile modulus of 11 ± 1 GPa, surpassing similar composites in the literature. These enhancements can be attributed to the alkaline (NaOH) treatment, which improved the fiber-matrix bonding by increasing surface roughness and removing impurities, thus enabling better load transfer between the fibers and resin. The NaOH treatment activated hydroxyl groups on the fiber surface, which significantly improved tensile strength and modulus. The hybridization with Phoenix Sylvestris fibers also contributed to the improved mechanical performance by enhancing the load-bearing capacity and ensuring even stress distribution. Furthermore, the incorporation of glass fiber added rigidity and strength, further enhancing the composite's tensile properties. The significant improvement in tensile properties highlights the effectiveness of combining natural and synthetic fibers. The glass fibers, in particular, compensated for any weaknesses in the natural fibers, contributing to the composite's overall stiffness and tensile strength. Additionally, the elongation at a break of 14 ± 1 % indicates that the composite offers a balanced combination of strength and ductility, making it suitable for dynamic load-bearing applications.

This research demonstrates that the hybrid composite can compete with conventional synthetic composites like GFRP, offering a more sustainable and biodegradable alternative. The high tensile strength, combined with the environmental advantages of natural fibers, makes this composite ideal for use in automotive, packaging, and structural applications, where lightweight, durable materials are essential. These findings underscore the critical role of fiber surface modification and hybridization in advancing the mechanical performance of bio-based composites, paving the way for their broader application in engineering sectors.

Similar studies on banana or coconut fibers report tensile improvements post-alkali treatment [14], matching or surpassing these composites' performance. Alkali treatment, known to enhance fiber-matrix adhesion [15], is validated by this study's increased tensile strength and modulus. This gradual enhancement suggests robust load-bearing capacity, with 14 ± 1 % elongation indicating balanced strength and ductility. Compared to GFRP, this hybrid composite offers similar mechanical properties with added sustainability and biodegradability benefits [16] making it suitable for automotive, construction, and packaging applications. Fig. 2 and Fig. 3 display the tensile strength and elongation at break, and tensile modulus, respectively.

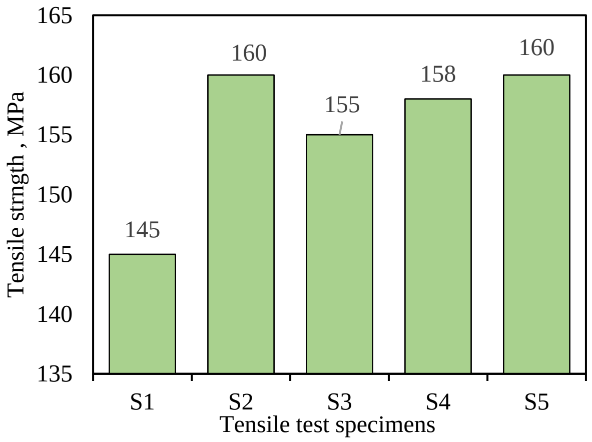

Fig. 2. Tensile strength of the prosposis hybrid composite

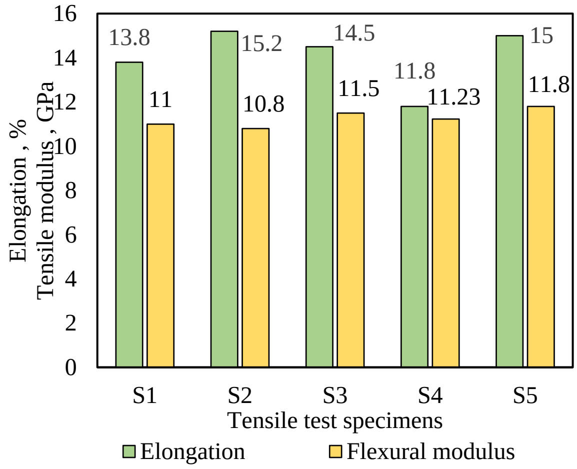

Fig. 3. Elongation and tensile modulus of the composite

4.2. Flexural strength

The flexural strength of the hybrid composite made from Prosopis Juliflora and Phoenix Sylvestris fibers, reinforced with glass fiber and epoxy resin, reached an average of 194.6 ± 3.4 MPa, showing significant improvement in bending resistance. This enhancement is primarily due to the alkaline treatment (NaOH), which increases the surface roughness of the natural fibers, improving the interfacial bonding between the fibers and the epoxy resin. Stronger adhesion led to better load transfer, allowing the composite to withstand higher bending forces. The careful stacking sequence of the natural fibers and glass fiber created a synergistic effect that promoted even stress distribution, reducing the risk of fracture under flexural loads. The inclusion of glass fiber also contributed to the composite's stiffness, further enhancing its flexural properties. The results emphasize the critical role of fiber surface modification and optimal fiber alignment in achieving high flexural strength. Compared to conventional natural fiber composites, this hybrid composite performs exceptionally well in bending scenarios, making it suitable for automotive, structural, and packaging applications that require a balance of strength and stiffness. The ability to resist deformation under bending stresses highlights its potential for load-bearing applications.

The flexural test offers vital insights into the composite's resilience under bending, simulating real-world conditions where materials endure both tensile and compressive stresses. This makes the composite particularly useful in applications such as automotive body parts, building panels, and bridge components. Future studies could explore the thermal and moisture resistance of the composite, expanding its application in environments exposed to varying climatic conditions and further solidifying its use in outdoor and structural applications. Additionally, the efficacy of the stacking sequence in augmenting both flexural strength and modulus, as elucidated, mirrors the obtained results. Comparative analysis with the research of other scholars further substantiates the superiority of the Prosopis juliflora hybrid composite in flexural performance within the realm of natural fiber composites [17]. The documented benefits of alkali treatment on flexural properties validate the observed enhancements in flexural strength and modulus. This gradual amelioration underscores the composite's potential for diverse engineering applications, offering mechanical attributes akin to conventional glass fiber-reinforced plastics (GFRP) while affording additional sustainability and biodegradability benefits Fig. 4 and Fig. 5 show flexural strength and flexural modulus of composite.

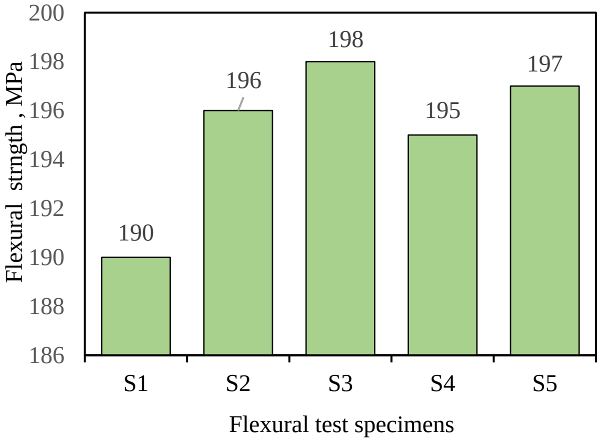

Fig. 4. Flexural strength of hybrid composite

4.3. Impact strength

The evaluation of impact strength for the Prosopis Juliflora hybrid composite, employing an Impact testing machine by ASTM D 256 standards and emphasizing the Izod test method, yielded an energy absorption of 15.22 ± 1.78 J, visually represented in Fig. 6 and Fig. 7 depicting impact resistance and force per specimen.

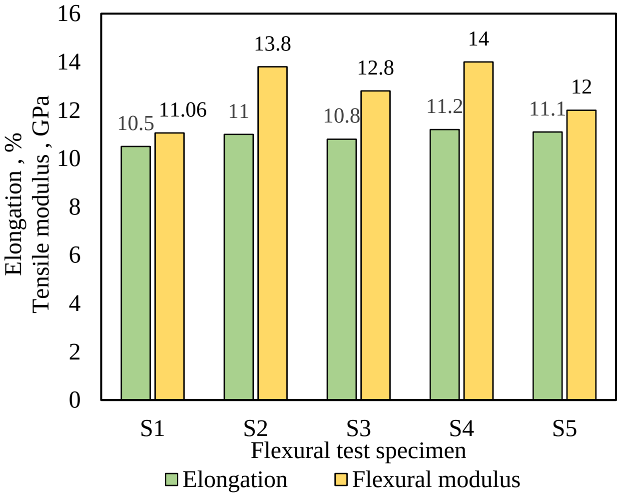

Fig. 5. Elongation and flexural modulus of composite

The study delved into the nuanced interplay of fiber and resin volume fractions, accentuating the intricate balance requisite between fiber reinforcement and resin matrix toughness. Corresponding with prior research, the observed impact strength concurred with expected enhancements attributed to the integration of Prosopis Juliflora fibers, thus reaffirming observations on heightened impact performance [18].

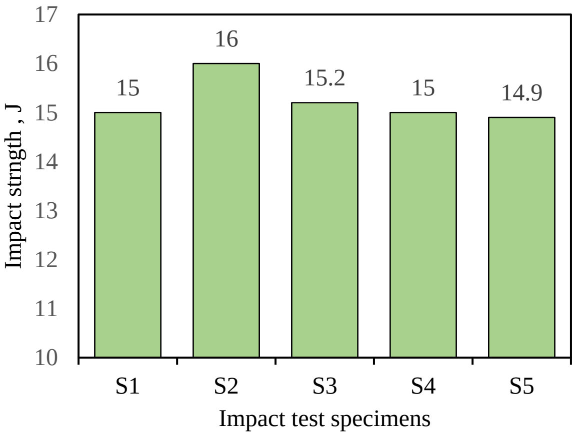

Fig. 6. Impact strength of hybrid composite

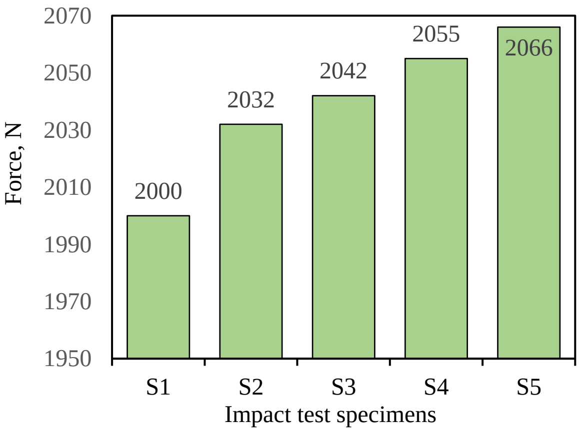

Fig. 7. Impact force hybrid composite

The efficiency of alkali-treated Prosopis Juliflora fibers lends further credence to the study's outcomes. Earlier works extolled the impact resistance benefits of Prosopis Juliflora fibers and fiber treatment methodologies, while the recorded energy absorption, commensurate with analogous composites, underscored the hybridization strategy's effectiveness in augmenting impact performance [19]. The delineated impact strength not only validates the Prosopis Juliflora hybrid composite's applicability for impact-resistant contexts but also underscores the symbiotic relationship between fiber reinforcement and resin toughness, emphasizing the pivotal role of material composition in delineating impact resistance. Further inquiry into diverse fiber and resin formulations may optimize composite performance for bespoke applications.

4.4. Hardness of the composite

The evaluation of hardness properties in the Prosopis juliflora hybrid composite utilized Rockwell hardness assessment, with Fig. 8 presenting the resultant hardness values.

Fig. 8. The hardness of the hybrid composite

The findings indicate that parameters such as fiber orientation, strength, and density are pivotal determinants of the composite's hardness characteristics, influencing its response to applied indentation forces during testing. This observation is consistent with prior studies, which underscored the significant role of fiber properties in composite hardness. Moreover, research emphasized the impact of material density on hardness properties [20]. The observed relationship between these factors and composite hardness reaffirms expectations derived from earlier research. Additionally, the study's outcomes align with the broader understanding that fiber alignment and strength profoundly influence composite hardness. Thus, the hardness assessment unveils the intricate interplay of material characteristics in shaping the composite's mechanical profile, offering valuable insights for engineering applications.

4.5. Delamination test

A delamination test was conducted to evaluate the internal strength of the composite and discern its failure mode under heavy loads, which commonly induce layer separation, under ASTM D5528 standards. This delamination results in a loss of internal strength due to physical separation between layers. A continuous load was applied to the composite laminate until it fractured and delaminated, allowing determination of the uniform breaking load. Fig. 9 illustrates the delamination stress of the Prosopis Juliflora hybrid composite. This testing protocol is consistent with prior studies, emphasizing the importance of understanding failure modes and internal strength in composite materials. Additionally, underscored the necessity of adhering to standardized testing procedures, such as ASTM standards, for accurate evaluation of composite performance. The observed delamination stress provides valuable insights into the composite's structural integrity under heavy loading conditions, aligning with anticipated outcomes based on earlier research [21].

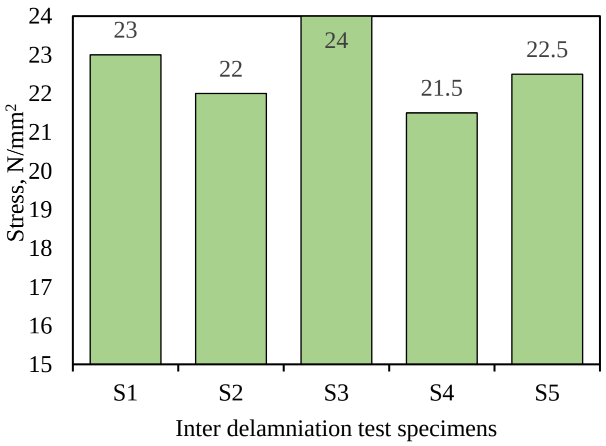

Fig. 9. Delamination stress hybrid composite

Table 1 shows that the hybrid composite exhibits high tensile and flexural strength, along with superior impact resistance and reduced delamination under heavy loads. We took five specimens to test for all tests and evaluated the average value for a result. Hybridization produces a high hardness value. The Prosopis Juliflora hybrid composite enhances automobile applications.

Table. 1. Mechanical properties of Prosopis juliflora hybrid composite

Mechanical properties of Prosopis juliflora hybrid composite	Mean and average values
Tensile strength, MPa	155 ± 4.4
Flexural strength, MPa	194.6 ± 3.4
Impact strength, J	5.22 ± 1.78
Interlamination stress, N/mm^2	22.6 ± 1.4
Hardness, VPN	40 ± 3

4.6. Microstructural analysis

The microstructural analysis of the Prosopis Juliflora and Phoenix Sylvestris hybrid composite was carried out using Scanning Electron Microscopy (SEM), which provided crucial insights into the fiber-matrix interaction, fiber alignment, and failure mechanisms. The SEM images, taken at magnifications ranging from 200^x to 1000^x, allowed for a detailed examination of the composite’s surface morphology and fracture behavior after mechanical testing. Fig. 10 shows the tensile fracture surface, the SEM image reveals both clean fiber breakage and fiber pull-out, indicating that while some fibers fractured under tensile stress, others were pulled out from the matrix due to insufficient bonding. This correlates with the tensile strength results, where improved bonding was observed, but there were areas with debonding that limited the composite's performance.

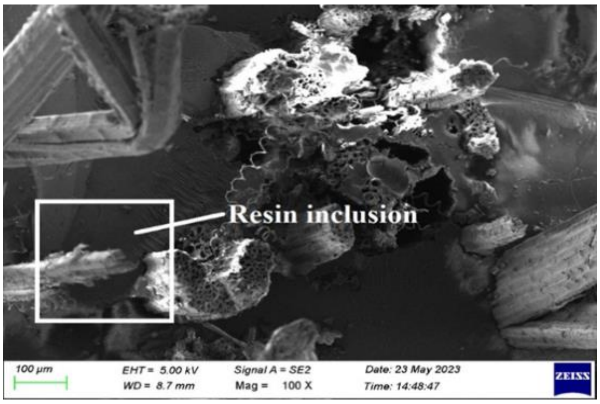

Fig. 10. Tensile fracture image

Fig. 11 the image shows the flexural fracture surface and fiber breakage along with resin cracking, suggesting that the composite endured significant bending stress. The balance between fiber pull-out and resin fracture aligns with the high flexural strength observed, where the fibers and matrix share the load evenly.

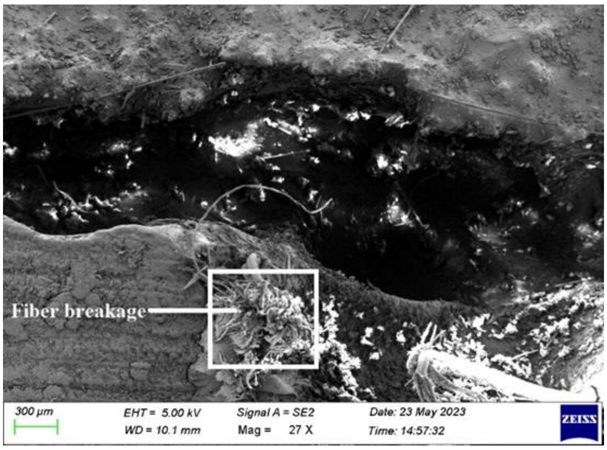

Fig. 11. Flexural fracture image

Fig. 12 reveals dispersed fibers with noticeable fiber pull-outs and voids, which compromised the composite’s ability to absorb energy during the impact test. These voids likely formed due to improper preparation, leading to reduced impact strength despite the overall improvement in mechanical properties. Additionally, the delamination surface, after heavy loading, shows increased resin accumulation and layer separation between the fibers, which correlates with the delamination test results. While the composite demonstrated good interlayer strength, localized areas of weak bonding were observed, contributing to delamination under extreme loads. Fig. 13 shows the delamination stress fracture image of a hybrid composite [22]. The SEM analysis provided a strong correlation between the composite's microstructure and its mechanical properties. The presence of fiber pull-out and voids in the tensile and impact specimens pointed to insufficient fiber-matrix adhesion in certain regions, which negatively impacted the energy absorption and strength.

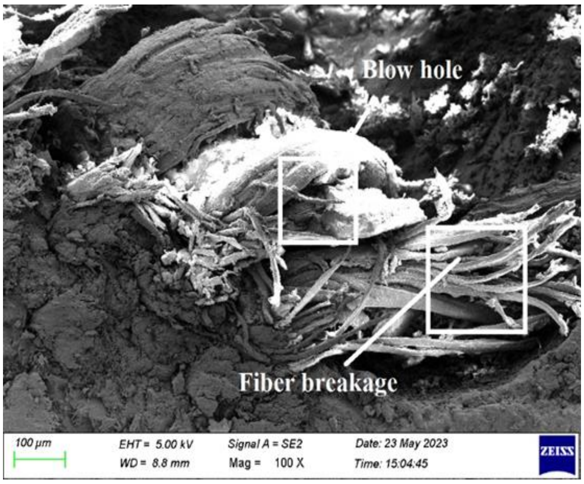

Fig. 12. Fracture of impact test

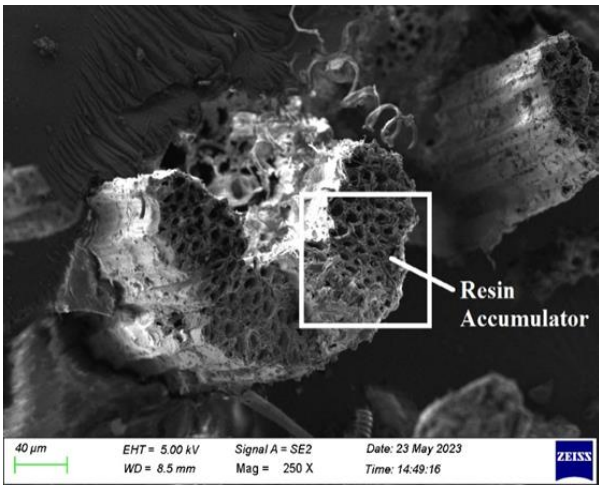

Fig. 13. Delamination fracture image

Conversely, the fiber breakage and resin cracking in the flexural specimens indicated efficient load transfer and higher bending resistance, explaining the superior flexural strength of the composite [23]. The delamination results also reflected the SEM findings, where the integrity of the layers was strong but showed localized weaknesses at the interface [24]. This microstructural analysis is significant in highlighting the effectiveness of NaOH treatment in improving fiber-matrix adhesion, resulting in enhanced mechanical properties. However, the presence of voids and inconsistent resin distribution indicates a need for further optimization of the fabrication process to minimize defects. Proper fiber distribution, orientation, and matrix penetration are essential for uniform stress distribution, which reduces premature failure under mechanical stress. The scope of this analysis extends to enhancing the understanding of how fabrication techniques, fiber treatments, and stacking sequences impact the composite’s overall performance. SEM is an invaluable tool for visualizing microscopic defects such as voids, fiber pull-outs, and matrix cracks, all of which influence the mechanical behavior of the composite. These insights are crucial for improving the design of composite materials for engineering applications, such as automotive, aerospace, and structural materials, where understanding the micro-level failure mechanisms is key to developing more robust materials. Future work should focus on refining the fabrication techniques, such as employing vacuum-assisted processes to reduce void formation and ensure better resin infiltration. Higher magnification SEM analysis could also be useful to explore nano-level interactions, providing further avenues for enhancing composite performance under dynamic loading conditions. The current findings elucidate the composite's microstructural features and offer valuable insights into its mechanical performance, aligning with anticipated outcomes based on earlier research.

5. CONCLUSIONS

This study has demonstrated the significant potential of hybrid composites made from Prosopis juliflora and Phoenix sylvestris fibers reinforced with glass fiber and epoxy resin, showcasing impressive mechanical properties, including tensile strength (155.6 MPa), flexural strength (194.6 MPa), impact strength (15.22 J), hardness (40 VHN), and delamination stress (22.6 N/mm²). The application of alkaline treatment notably improved interfacial bonding between the fibers and the resin matrix, enhancing mechanical performance, while NaOH-treated natural fibers exhibited increased strength and durability, confirmed by scanning electron microscopy (SEM). This research presents a novel approach to utilizing these underexplored natural fibers, offering a sustainable alternative to synthetic materials in engineering applications. Future research could explore enhancing water resistance, thermal stability, and fire resistance, as well as optimizing fiber treatment and investigating biodegradability to confirm the composites' eco-friendliness. Additionally, integrating this hybrid composite into automotive parts could leverage its impact resistance and lightweight properties, thereby paving the way for advanced engineering applications that prioritize sustainability.

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