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Research Article

Quasi-Static Puncture Performance of Soya-Epoxy Composites Reinforced with Jute, Glass, and Nano-Carbon Fibers: Influence of Indenter Shape and Environmental Conditions

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ABSTRACT

The growing need for sustainable and impact-resistant materials has driven research into natural fiber-reinforced composites for lightweight and durable applications. This study investigates the quasi-static puncture resistance of natural fiber-reinforced soya-based composites reinforced with jute, glass, nano-carbon, and glass woven fibers. Puncture tests were conducted using flat, ball, and cone-shaped indenters to analyse the influence of indenter geometry on the mechanical response of the composites. Results revealed that the flat indenter, with a larger contact area, achieved the highest peak load (2705.750 N) by distributing force across more material, while the ball indenter recorded moderate peak loads (1792.00 N), and the cone indenter, with a concentrated tip, exhibited the lowest peak loads (1608.25 N) due to focused stress. Microstructural analysis post-testing highlighted deformation, crack initiation, pull-out, and delamination, elucidating the failure mechanisms. These findings underscore the critical role of indenter shape, reinforcement type, and composite properties in determining puncture resistance, offering insights into the structural behaviour and potential applications of soya-based composites in impact-resistant designs.

Keywords: Quasi-static puncture resistance; Natural nano fiber-reinforced composites; Soya-epoxy based composites; Indenter geometry; Microstructure.

1. INTRODUCTION

Natural fiber-reinforced composites are becoming more and more popular for applications requiring resistance to impact due to their lightweight and environmentally friendly qualities. This work highlights how indenter geometry affects the mechanical performance of soya-epoxy composites reinforced with jute, glass, and nano-carbon fibres by examining their quasi-static puncture resistance. Natural fiber-reinforced composites are gaining attention as sustainable alternatives to traditional synthetic composites due to their eco-friendly and biodegradable nature (Prasad *et al.* 2024). Conventional composites, typically reinforced with petroleum-derived fibers and resins, pose significant environmental challenges, including high production energy consumption, lack of biodegradability, and difficulties in recycling (Musa and Onwualu, 2024).

In contrast, natural fiber composites, which incorporate renewable resources like plant-based fibers, offer advantages such as low density, cost-effectiveness, and biodegradability, addressing global concerns like resource depletion, environmental degradation, and climate change by reducing dependency on synthetic materials (Thapliyal *et al.* 2023). Among natural fibers, jute has emerged as a promising candidate due to its high specific strength, good toughness, and wide availability.

The integration of synthetic reinforcements, such as chopped glass fibers or woven glass fibers with natural fibers further enhances mechanical properties, making these composites suitable for high-performance applications (Zaman and Rahman, 2024; Sathishkumar *et al.* 2014).

This study investigates the quasi-static puncture resistance of soya-based composites reinforced with natural fibers, emphasizing structural integrity and energy absorption under varying penetration conditions (Moshkbid *et al.* 2024). Natural fiber composites are not only less energy-intensive to produce but also utilize renewable raw materials and decompose naturally, reducing non-recyclable waste in the environment (Mohanty *et al.* 2022). The incorporation of soya-based resins, derived from renewable agricultural practices, enhances sustainability by minimizing greenhouse gas emissions during production and reducing reliance on petroleum-based polymers (Amulya *et al.* 2021). Quasi-static puncture testing, a critical method for assessing mechanical responses under localized loading conditions, provides insights into the energy absorption, failure mechanisms, and load-bearing capacities of materials (Mani *et al.* 2024).

In this study, flat, ball, and cone indenters were used to evaluate puncture resistance, with the flat indenter showing the highest peak load due to its greater contact area, which disperses force over a broader region (Mayya *et al.* 2021). The type and architecture of fiber reinforcement significantly influence the mechanical performance and environmental impact of composites (Sethi and Ray, 2015). Jute fibers demonstrated excellent energy absorption and ductile failure characteristics under puncture loading due to their inherent toughness and plastic deformation.

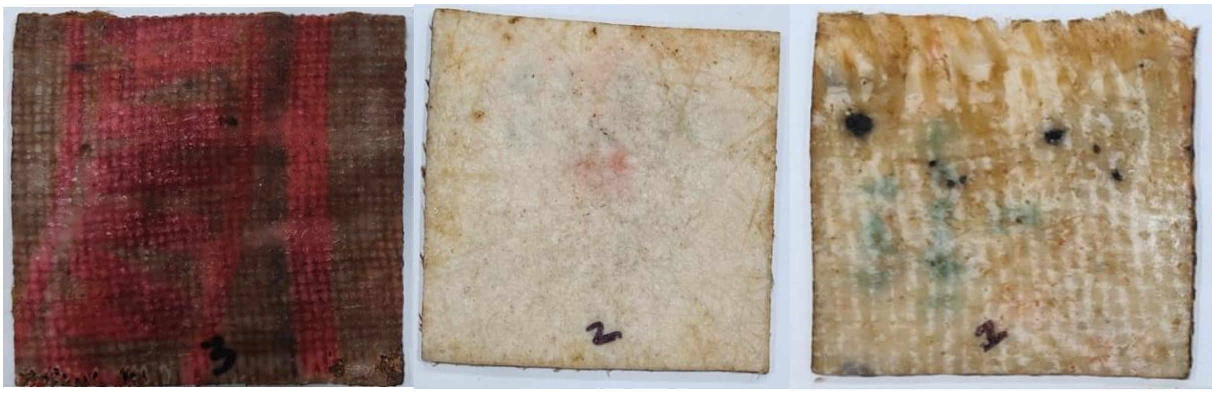
Their biodegradability ensures minimal environmental impact at the end of their lifecycle (Andrew *et al.* 2019). Conversely, chopped glass fibers exhibited brittle fracture mechanisms with limited energy absorption, while woven glass fibers provided improved puncture resistance due to their interwoven structure, which distributes stresses more uniformly. Soya-based resins, used as the matrix material, effectively bonded the fiber reinforcements and transferred stresses during loading, ensuring efficient load distribution (Zhao *et al.* 2024). As eco-friendly substitutes for petroleum-based polymers, soya-based resins enhance the mechanical performance of the composites while supporting sustainability goals (Chaudhary *et al.* 2024). The combination of natural fibers, synthetic reinforcements, and soya-based resins creates versatile composites suitable for applications requiring structural integrity and puncture resistance, such as ballistic panels, protective gear, automotive parts, and aerospace components (Wagner and Wollmann, 2013).

The flat indenter demonstrated the potential to optimize structural integrity by requiring more energy to puncture the composite due to its wider contact surface, while the ball and cone indenters provided insights into the effects of contact area and stress concentration on failure mechanisms. This study highlights the importance of balancing mechanical performance and environmental impact when designing composite materials. Industries can reduce the environmental footprint of composites without compromising quality by prioritizing natural fibers and sustainable resins. The findings provide valuable insights into optimizing fiber and composite designs for applications requiring durability and high impact resistance. By advancing the understanding of quasi-static puncture behaviour, this research contributes to the development of high-performance, lightweight materials that combine excellent mechanical properties with environmental sustainability. The insights gained from this study have significant implications for the development of lightweight, high-performance materials that combine environmental sustainability with superior mechanical properties. By leveraging the unique characteristics of natural and hybrid composites, industries can achieve sustainable solutions that meet the demands of modern engineering challenges.

2. MATERIAL AND METHODS

2.1 Materials

The images of three different soya-epoxy based composite materials as shown in Fig.1



(a) (b) (c)

Fig. 1. Schematic representation of the materials: (a) Jute (b) Glass carbon fiber (c) Glass woven fiber

Each composite is reinforced with a distinct type of fiber: Fig.2(A) shows jute fiber reinforcement, Fig. 2(B) features chopped glass fiber, and Fig. 2(C) highlights woven fiber. These fibers are selected based on their mechanical properties and suitability for specific applications. Jute fiber offers eco-friendliness and cost-effectiveness, while chopped glass fiber enhances strength and impact resistance. Woven fibers provide superior structural integrity and uniform load distribution. Three types of hybrid composites were fabricated for this study, as shown in Fig.2: (A) jute/jute/jute, (B) chopped glass fiber (600 GSM)/jute/chopped glass fiber, and (C) woven glass fiber (600 GSM).

Layer 1	Jute	Chopped Glass Fiber	Woven Glass Fiber
Layer 2	Jute	Jute	Jute
Layer 3	Jute	Chopped Glass Fiber	Woven Glass Fiber
	A	B	C

Fig. 2. Schematic representation of the stacking sequence of materials: (a) Jute/Jute/Jute, (b) Glass Carbon Fiber/Jute/Glass Carbon Fiber, and (c) Glass Woven Fiber/Jute/Glass Woven Fiber

These composites were produced using soya epoxy as the matrix, with woven and chopped glass fibers as reinforcements. The fabrication process involved a hand layup method followed by compression molding. The layers were compressed at a temperature of 80°C and a pressure of 5 MPa for 4 hours. The resulting laminates, each 3 mm thick, were cut into 90 mm × 90 mm sections using a band saw for further testing and analysis..

2.2 Experimental Method

Fig.3 illustrates the experimental setup for evaluating the puncher test with different indenters.

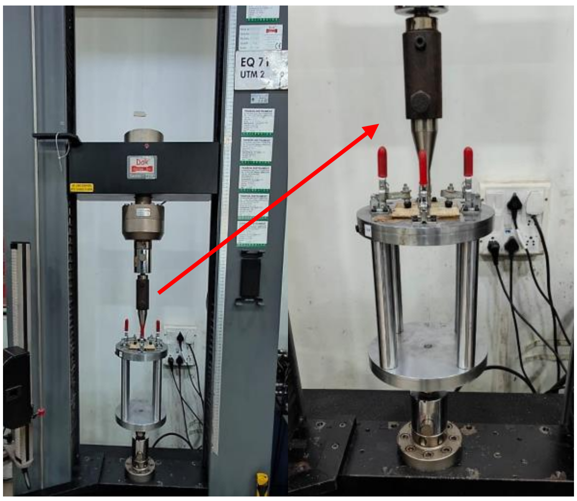


Fig. 3. A and B is Setup for the Puncher Test using a universal testing machine and Shows a closer view of the testing jig or fixture

The universal testing machine (UTM) equipped with a Dak system of 100kN load cell for high-precision testing is depicted in Fig. 3(A). A closer view of the punching assembly with sample holder with a material's penetration resistance. is shown in Fig. 3(B),

2.3 Mechanical Properties Using Indentation Techniques

Fig.4, shows the damage caused to materials by three types of indenters: flat, cone, and ball. Each row highlights the resulting deformation and puncture area under different indenter geometries, with images emphasizing the variations in damage patterns.

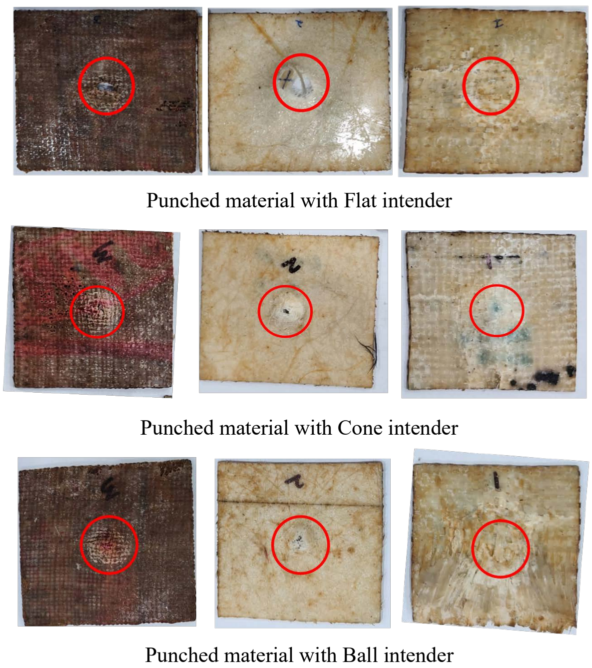


Fig. 4 . Materials after the impression of the Ball Indenter Jute, Glass Carbon Fiber, and Glass Chopped Fiber, along with Ball Indenter Setup

The different indenter shapes affect the puncture resistance of materials. A flat indenter spreads the force over a larger area, causing wider surface deformation. In contrast, cone and ball indenters focus the force, leading to more concentrated damage and varying penetration depths shown in Fig.4 This analysis helps understand how materials fail under localized forces, providing guidance for designing tougher, impact-resistant materials.

3. RESULT AND DISCUSSION

3.1 Flat Intender

To evaluate the mechanical characteristics and puncture resistance of various materials, particularly jute, glass composite fibre (G.C.F.), and glass wool fibre (G.W.F.)

under controlled, slow-loading conditions, a quasistatic puncher test was performed in Fig.5, The findings showed notable differences in the materials' resistance to puncture forces.

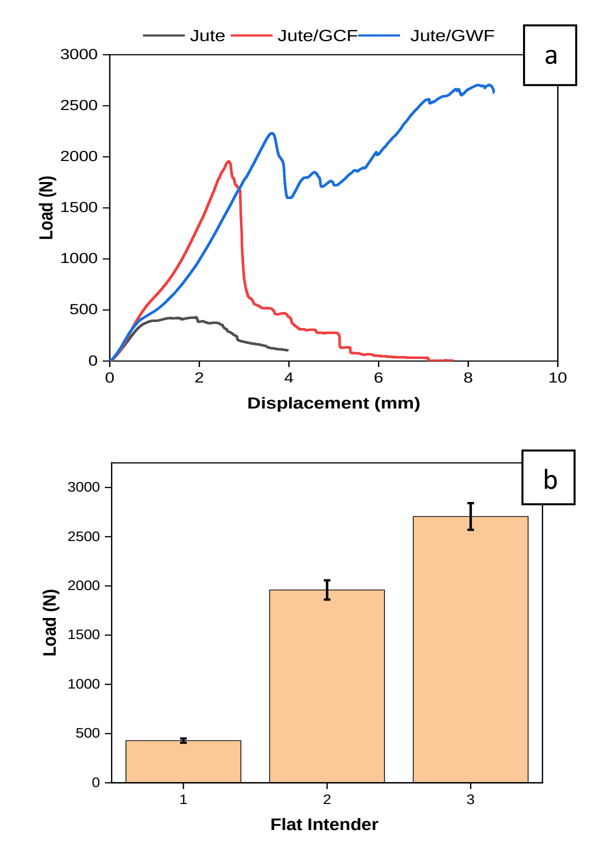


Fig. 5. Load vs Dispalcement and, illustrating error bar of the composites of flat intender

A load-bearing capability of 300 N at a displacement of 4 mm, jute showed the lowest puncture resistance in Fig. 5(A), suggesting that it has a limited capacity to withstand mechanical stress before failing. With a load of 2000 N at 7.5 mm displacement, on the other hand, G.C.F. showed a significantly stronger resistance to puncture, demonstrating the improved strength and deformation capacity of glass composite fibres. However, at a maximum load of 2250 N at 9 mm displacement, G.W.F. had the strongest puncture resistance, indicating higher toughness and energy absorption prior to failure. These findings highlight the important distinctions in mechanical performance between natural and synthetic fibres, underscoring the necessity of choosing materials according to the demands of particular applications. Although jute might be more G.C.F. and G.W.F. provide improved durability and puncture resistance, making them more appropriate for high-performance applications in sectors like construction, automotive, and protective gear. They are also appropriate for low-stress applications or ecologically sensitive designs. The force (in Newtons) needed to penetrate three distinct materials using a flat indenter is shown in the bar chart of Fig.5(B). Material 1 has the weakest mechanical integrity and the lowest puncture resistance, at about 500 N. With a weight of about 2000 N, Material 2 shows a noticeably stronger resistance, whereas Material 3 shows the highest resistance, just over 2000 N. Materials 2 and 3 barely differ from one another, however Materials 3 performs slightly better than Materials 2.

3.2 Cone Intender

The effect of the cone intender of load-displacement curves for various fiber-reinforced soy-based composites is shown in Fig. 6 along with a comparison of peak loads for Jute, Jute/Glass Chopped Fibre (G.C.F), and Jute/Glass Woven Fibre (G.W.F) reinforced composites.

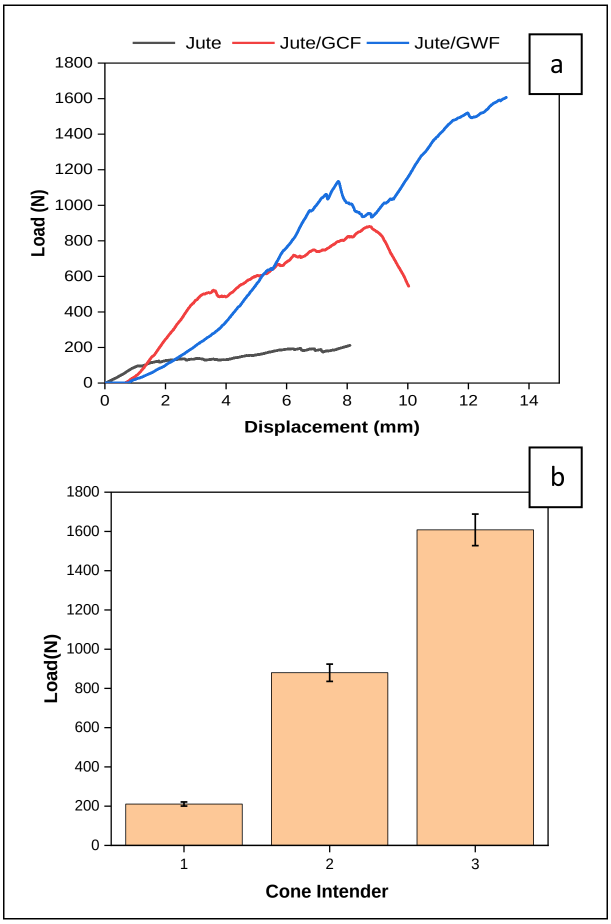


Fig. 6. Load vs Dispalcement and, illustrating error bar of the composites of cone intender

The performance of the materials varied significantly, according to the data, with jute showing the lowest penetration resistance and supporting a maximum load of 100 N at an 8 mm displacement. This demonstrates that it is only appropriate for low-stress or environmentally friendly applications due to its limited mechanical strength and substantial deformation under low stress. Because of the reinforcement that its glass fiber-polymer matrix composition provides, G.C.F. showed much higher performance in Fig.6(A), withstanding a load of 500 N at 8.5 mm displacement, demonstrating its superior structural integrity and energy absorption capabilities. G.W.F. fared better than both materials, withstanding the maximum load of 1100 N at a displacement of 12 mm. This demonstrated its remarkable resilience and ability to dissipate energy under stress, which makes it perfect for high-performance applications like insulation. systems for protection and packing. By imitating actual impact situations, the cone-shaped indenter concentrated stress at a particular location, offering insights into the materials' localised failure mechanisms.

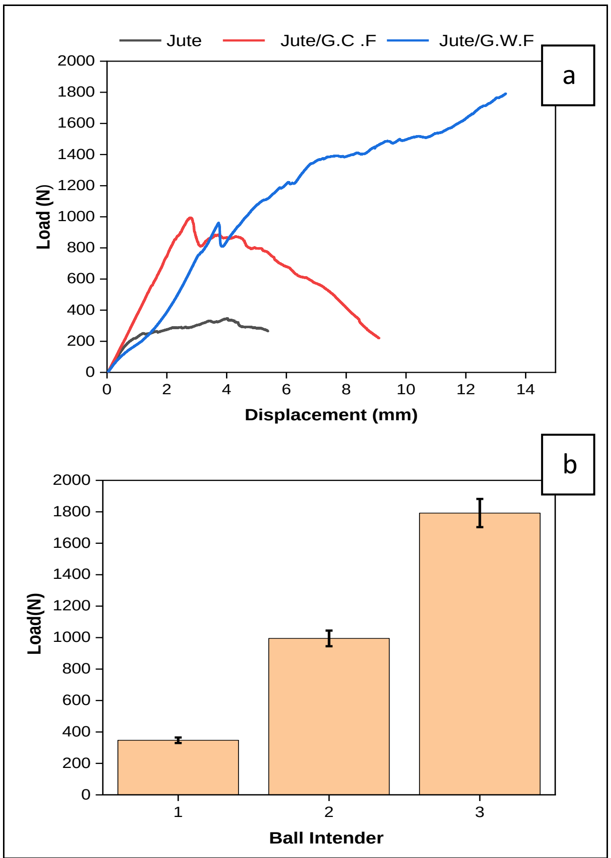


Fig. 7. Load vs Dispalcement and, illustrating error bar of the composites of ball intender

The findings demonstrate the superior performance of synthetic materials such as G.C.F. and G.W.F. The Fig.6(B) displays the three materials' puncture resistance as determined by a cone indenter test. With its poor mechanical strength, Material 1 performs the worst, withstanding only about 200 N. With its ability to handle about 1000 N, Material 2 shows a notable improvement in structural integrity. Material 3 performs better than the others, demonstrating exceptional toughness and longevity by withstanding roughly 1600 N. These results show a steady increase in load-bearing capability, with the first material better suited for low-stress or lightweight applications and the third material best suited for high-stress applications. For situations requiring intermediate strength, the second material is perfect since it provides a balanced performance. In order to optimise material qualities for particular applications, the research highlights the significance of composition and reinforcement.

3.3 Ball Intender

To evaluate the mechanical characteristics and penetration resilience of jute, glass composite fibre (G.C.F.), and glass wool fibre (G.W.F.) under gradual, controlled loading, a quasistatic puncher test using a ball-shaped indenter was conducted as shown in Fig.7.

The Fig.7(A) findings demonstrated distinct material behaviours, with jute showing moderate resistance, enduring a peak load of 200 N at a displacement of 5.5 mm, indicative of its fibrous nature and restricted strength, making it apt for low-stress, environmentally-conscious uses. Conversely, G.C.F. exhibited a lower load capacity of 100 N at a displacement of 9 mm, suggesting significant deformation and a vulnerability to concentrated spherical forces, underscoring the need for refinement in fiber orientation or matrix integration. G.W.F. showcased the highest performance, sustaining a load of 900 N at a displacement of 12 mm, highlighting its superior toughness, energy dissipation, and adaptability under mechanical stress, rendering it ideal for applications such as insulation, cushioning, and protective barriers. The ball indenter's curved design emphasized the materials' localized stress distribution capabilities, revealing G.W.F. as the most robust material, while jute and G.C.F. displayed inherent limitations. These observations emphasize the critical role of material selection in application-specific contexts and suggest avenues for enhancing jute's mechanical attributes through composites and advancing G.C.F. through structural optimization to meet stringent industrial demands. In the Fig.7(B)Three materials' resistance to punctures using a ball indenter is displayed in the chart. With a resistance of about 400 N, Material 1 performs the worst, demonstrating its low mechanical strength. With a strength of about 1000 N, Material 2 shows a significant improvement, indicating improved structural qualities. In contrast, Material 3 exhibits exceptional toughness and durability, achieving the maximum resistance, handling around 1800 N. With Material 1 being appropriate for low-stress applications, Material 2 providing balanced qualities for moderate-stress situations, and Material 3 emerging as the most reliable option for high-stress or critical applications, these results show a progressive increase in mechanical performance. The importance of material composition and reinforcing in maximising puncture resistance is highlighted by this analysis.

4. MICROSTRUCTURE ANALYSIS

Microstructural pictures of a jute fibre composite material both in its initial condition and following a piercing test are shown in Fig.8. The post-test photographs emphasise the failure mechanisms of the material under mechanical loading by revealing deformation, fracture start, and possible fibre pull-out or delamination, whereas the pre-test images display a uniform and undamaged structure.

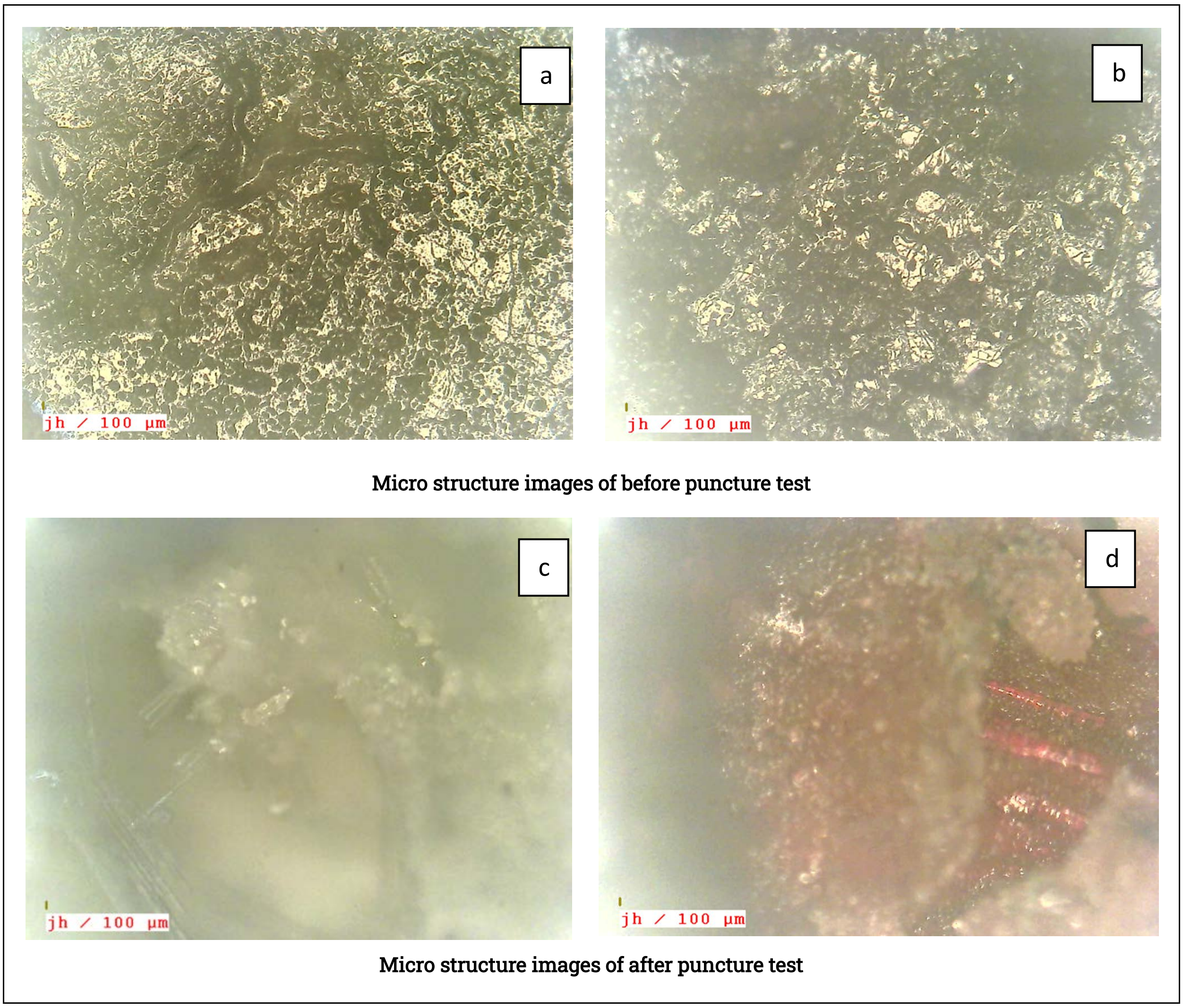


Fig. 8. The microstructure view of jute composite

The surface of Fig.8(A) is rough, crystalline, and amorphous, exhibiting particular characteristics such as cracks, pores, and inclusions that could be attributed to material attributes or processing conditions. In contrast, Fig.8(b) displays a smoother, more homogeneous surface, with the appearance of fewer or no cracks and voids, suggesting alterations possibly due to environmental exposure, ageing, or changes in processing conditions. These surface modifications are likely caused by factors such as prolonged exposure to heat or humidity, which could affect material properties and performance. Since surface morphology often reveals insights into material performance and degradation mechanisms, understanding these changes is crucial for evaluating the durability and reliability of materials. Fig.8(C) exhibits a rough, crystalline surface with visible cracks and pores, indicating potential processing-related imperfections. In Fig. 8(D) displays a smoother, more uniform surface with fewer visible defects, suggesting possible surface modification or aging effects. These variations in surface morphology may be attributed to factors such as different treatments, environmental exposure, or the material's aging process. Understanding the surface morphology is critical for evaluating the material's performance, especially in applications where durability and resistance to environmental factors are key.

5. CONCLUSION

The findings of this study demonstrate that the quasi-static puncture resistance of natural fiber-reinforced soya-based composites is strongly influenced by the type of fiber reinforcement, fiber architecture, and indenter geometry. The flat indenter achieved the highest resistance due to its ability to distribute load over a larger area, while the cone indenter exhibited the lowest resistance due to stress concentration at its sharp tip. Among the reinforcements, woven glass fibers provided superior puncture resistance owing to their interlocking structure, while jute fibers displayed ductile failure with significant energy absorption, and chopped glass fibers showed brittle fracture behaviour. Microstructural analysis revealed deformation, crack propagation, fiber pull-out, and delamination as primary failure mechanisms, varying with fiber type and indenter shape. These results emphasize the importance of selecting appropriate fiber architectures and optimizing composite designs to enhance performance under mechanical loading, offering valuable insights for developing impact-resistant and structurally robust soya-based composites.

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CONFLICT OF INTEREST

The authors declared no conflict of interest in this manuscript regarding publication.

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