Journal of Materials and Environmental Science
ISSN : 2028-2508
e-ISSN : 2737-890X
CODEN : JMESCN

J. Mater. Environ. Sci., 2023, Volume 14, Issue 10, Page 1171-1184

http://www.jmaterenvironsci.com

Basalt and Jute Hybrid Epoxy Composites' Mechanical and Morphological Characteristics

Sadashiva K.[1]*, Pradeep Kumar P.[2], Rajeshwari P.[3], Tarakeshwar Jane[1], Shashanka G.[4], Spoorthi M. J.[1]

[1]Department of Mechanical Engineering, Dr. Ambedkar Institute of Technology, Bengaluru, 560056, Karnataka, India
[2]Department of Mechanical Engineering, Government Polytechnic, Chamarajanagar, 571313, Karnataka, India
[3]Department of Industrial Engineering and management, Dr. Ambedkar Institute of Technology, Bengaluru, 560056, Karnataka, India
[4]Department of Mechanical Engineering, Parul University, Vadodara, 391760, Gujarat, India
**Corresponding author, Email address: sadashiva41@gmail.com*

Received *07 Aug 2023,*
Revised *29 Sept 2023,*
Accepted *01 Oct 2023*

Keywords:
- ✓ *Hybrid composites;*
- ✓ *Basalt fiber;*
- ✓ *Jute fibers*
- ✓ *Mechanical Attributes;*
- ✓ *Morphology*

Citation*: Sadashiva K., Pradeep Kumar P., Rajeshwari P., Tarakeshwar Jane, Shashanka G., Spoorthi M. J. (2023) Basalt and Jute Hybrid composites Mechanical and Morphological Characteristics, J. Mater. Environ. Sci., 14(10), 1171-1184.*

Abstract: This study examined the characteristics of hybrid composites manufactured from basalt and jute fibres for prospective uses in fields needing materials that are light, ecologically friendly, and mechanically robust. Although the actual density of the composite was slightly lower than the theoretical density due to constrained gases during fabrication, study of density and void percentage showed that the inclusion of Basalt fibres enhanced the composite's density. According to the results of the tensile tests, alkali treatment and hybridization improved performance whereas water absorption had a negative impact on tensile strength. The highest tensile strength was found in the blend of laminate L3, which was a result of the jute fiber's hydrophobicity and moisture content. Additional flexural and impact tests supported the impact of water absorption on the mechanical characteristics of the composites. Additionally, SEM examination showed that alkali treatment enhanced the bonding of the fiber-matrix interface and roughened the fibre surfaces, improving the overall performance of the composites. The research offers priceless insights into the potential of basalt and jute hybrid composites as lightweight, ecologically benign, and mechanically durable materials for industrial applications.

1. Introduction

Researchers are looking at natural fibres as potential reinforcements for composite materials as a result of the growing interest in the development of environmentally friendly and sustainable technologies. Accessibility, low weight, corrosion resistance, and biodegradability are only a few advantages provided by natural fibres originating from plants and animals. They are seen as environmentally beneficial alternatives to synthetic materials (Balaji *et al,* 2023; Sadashiva *et al,* 2022; Aad *et al,* 2016; Elidrissi *et al,* 2012;). Jute and basalt fibres, which have special characteristics not seen in other natural fibres, have showed promise (Sadashiva et al, 2023). Natural fibres offer numerous benefits, but they also have certain drawbacks. An important drawback is their sensitivity to water absorption, which might impair the mechanical characteristics of the fiber-matrix composite. For natural fibre materials to be successfully used in the engineering and industrial sectors, it is crucial to understand how water absorption influences their mechanical characteristics. Natural fibre composites, such as Palmyra and glass fibre composites, have lower impact strength and greater water absorption, according to research comparing the water absorption behaviour of these materials (Sekar *et al,* 2022; Sadashiva *et al,* 2023; Akartasse *et al.* 2022a). Characterization approaches have been used to assess the physicochemical characteristics of natural fibres, including their cellulose concentration, lignin content, hemicellulose content, density, and crystallinity index. Due to their nature, which is high in cellulose, natural fibres are hydrophilic and absorb more water than synthetic fibres (Sathishkumar *et al,* 2013; Balaji *et al,* 2022; Akartasse , 2022b). Water absorption in natural fibre composites may result in fibre swelling and the development of micro cracks, which may affect the mechanical and dimensional characteristics of the composites (Sanjeevi *et al,* 2021). Since epoxy has many useful qualities, choosing the right matrix material is essential. Composites made of jute and basalt fibres have shown improved tensile behaviour, flexural modulus, and hardness qualities. Composites' flexural strength has enhanced thanks to the use of ceramic additives, while basalt fibres' tensile qualities have improved thanks to alkali treatment (Alsuwait *et al,* 2022; Sadashiva, *et al,* 2023; Khan *et al,* 2022). Hand-made epoxy composites made of hybrid basalt and jute fibres were created for this experiment (Lakshmi Narayana & Gopalan, 2023; Fiore & Calabrese, 2019). The composites underwent an alkaline treatment to change the surface characteristics of the fibres and get rid of contaminants. Measurements of density and void percent were performed to assess the composites' physical properties. In order to evaluate the composites' degrading qualities, water absorption was also applied to them. Tensile, flexural, and impact studies were used to examine the effects of alkaline treatment on the mechanical characteristics of water-absorbent composites. This research aims to shed light on the applicability of basalt and jute hybrid epoxy composites for diverse applications by thoroughly assessing the mechanical behaviour and water absorption capabilities. The research will aid in the creation of durable composite materials and promote their usage in sectors looking for materials that are light, environmentally friendly, and mechanically tough.

2. Experimental Methods

2.1 Materials

Jute and basalt fibres from Vruksha Composites in Guntur were used in the investigation, along with an Epoxy resin matrix from Ultra Nano Tech Pvt Ltd, Bengaluru. Through the use of water retting, both fibres were removed. It is emphasized how important jute and basalt fibres are to the investigation. Figure 1A displays the Basalt fibre, while Figure 1B displays the chopped jute fibres that were employed in the study. The mechanical and physical characteristics of jute and basalt fibres are shown in Table 1, respectively.

A. Basalt Fabric

B. Jute Fabric

Figure 1. A. Basalt Fabric B. Jute fabric

Table 1. Physical Properties of Basalt and Jute fibers

Properties	**Basalt**	**Jute**
Density (g/cc)	2.75	1.42
Tensile strength (MPa)	4840	450
Young's modulus (GPa)	89	60-95
Elongation (%)	3.15	2.9

2.2 Alkaline treatment

To enhance their qualities, alkaline treatment was applied to both jute and basalt fibres. A sodium hydroxide (NaOH) solution with 5% sodium hydroxide was used to chemically treat the fibres. As part of the alkaline treatment process, fibres were submerged in a glass container holding an alkaline solution. The fibres were soaked in the solution at room temperature for around two hours. The fibres were properly washed with water after the soaking procedure to remove any residual alkali (Jain *et al,* 2021). As a result, they were completely dry. The fibres were put in an oven that had been preheated to 70 0C to guarantee optimum drying. The goal of the alkaline treatment was to alter the fibres' surface characteristics, improving their compatibility with the polyester matrix and the overall effectiveness of the hybrid composites.

2.3 Composite fabrication

Epoxy hybrid composites were created utilizing the well-known hand lay-up method, as shown in Figure 2. Jute and basalt fibres were added in various amounts to the composites to reinforce them. According to the ASTM standard, a mould with the following measurements was used during the fabrication process: 300 mm in length, 300 mm in width, and 3 mm in height. A silicone release agent was sprayed to the surfaces of the mould to make it easier to remove the cured samples from it. The matrix resin, Epoxy reagent, was made and properly mixed with 10:1 by ratio hardener and 0.02% cobalt catalyst to get a homogeneous consistency. To get rid of any air bubbles, the liquid was subsequently degassed. The first layer of the composite material was created in the first stage by pouring the prepared matrix resin into the mould. Bidirectional basalt and jute fibres with a length of 300 mm were added on top of the initial layer. Any air pockets in the layer were removed by rolling it. Repeating this process allowed the composite to reach the necessary thickness. A sheet of plastic (polythene) was placed on top of the uncured uppermost layer before compressing the final layer. To provide a consistent thickness of 3 mm across the composite material, a load of 50 kilograms was utilised. After that, the material was allowed to cure for 24 hours at room temperature. The composites were then painstakingly taken out of the mould, as seen in Figure 2. Table 2 shows the proportions of basalt and jute fibres used to make composite materials.

Table 2. Laminate designation

Laminate	Fiber sequence
L1	B+B+B+B
L2	J+J+J+J
L3	B+J+J+B
L4	J+B+B+J

Only epoxy and basalt fibre composites are labelled (EB), while composites with epoxy, basalt fibre, and jute fibre are labelled (EBJ). According to the preliminary study, poor fibre distribution or moisture were caused when more than 15% of Basalt fibre was added to an epoxy matrix. Consequently, the fibre content was set at 15% for this investigation.

Figure 2. Hand Layup Process

3. Experimentation

3.1 Density and Void fraction

The ASTM D792 standard method, which is based on Archimedes' principle, was used to calculate the density of the polymer, fibre, and composite at room temperature (Sabarinathan *et al,* 2021). Each sample was weighed twice—once in air and once in water—in order to apply Archimedes' principle. Using a digital scale that was on hand in the lab, exact weight measurements were taken. The scale was modified because it didn't have a built-in attachment for suspending samples. The density of the sample in relation to the temperature of the water or the air might be determined by setting the assembly on the electronic balance's pan. The following equation was used to determine the theoretical density (ρ_{th}) of the composite:

$$\rho_{th} = (f_{fibre} \times \rho_{fibre}) + (f_{resin} \times \rho_{resin}) \qquad \textbf{Eqn. 1}$$

where f_{fibre} being Fraction of fibre content, f_{resin} being Fraction of resin content, ρ_{fibre} being Density of fibre, ρ_{resin} being Density of resin.

The actual density (ρ_{act}) was calculated as follows:

$$\rho_{act} = (\frac{A}{A-B}) \times \rho_{dw} \qquad \textbf{Eqn. 2}$$

where A being Weight of the sample in air, B being Weight of the sample in the water

The volume fraction of voids (V_v) was determined using the formula:

$$V_v = \frac{\rho_{th} - \rho_{act}}{\rho_{th}} \qquad \textbf{Eqn. 3}$$

The mechanical properties of composite materials can be significantly impacted by the presence of voids. Reduced fatigue resistance, increased sensitivity to moisture and erosion, and greater strength property variation can all be caused by an increase in void content. Therefore, it is crucial to comprehend the void content in order to appropriately assess the calibre of composites. The characteristics of composites may suffer if the vacuum volume fraction (Vv) increases, which is undesirable (Muktha *et al,* 2017).

3.2 Mechanical Characterisation

To assess the mechanical qualities of the composites, a number of tests including those for tensile strength, flexural strength, and impact strength were carried out. NIE Mysore provided the KIC-2-1000-C universal testing apparatus with a 100 kN load capacity for these tests. Tensile testing is shown in Figures 3A in accordance with ASTM D3039, whereas flexural testing is shown in Figures 3B in accordance with ASTM D790. Both tests were carried out at a constant strain rate of 1.5 mm/min. A Charpy Pendulum Impact Tester in accordance with ASTM D256 was used to gauge the impact strength. Tensile strength test specimens were 250 mm x 25 mm x 3 mm, whereas flexural strength test specimens were 100 mm x 12.5 mm x 3 mm. The impact testing specimens have dimensions of 65 mm by 10 mm by 3 mm.

A B

Figure 3. A. Specimen for tensile testing B. Specimen for Flexural testing

3.3 *Water absorption behaviour*

According to ASTM D-570, the water absorption behaviour of untreated and alkali-treated epoxy composites was assessed. Samples with various fibre weight ratios were submerged at room temperature in a beaker of distilled water to assess the kinetics of water absorption. At regular intervals of 24 hours, the samples were taken out of the water, wiped with tissue paper to remove any surface moisture, and then weighed with an electronic precision scale. This equation was used to calculate the percentage of water absorption:

$$\% \text{ Water Absorption} = \frac{M_t - M_o}{M_o} \qquad \textbf{Eqn. 4}$$

where, Mo being Initial weight of the specimen before immersion in water, Mt being Weight of the specimen after immersion in water.

It is able to learn more about the composite's capacity to absorb water and its resistance to moisture intrusion by examining the water absorption behaviour and determining the liquid ingestion rate. These findings provide light on the durability and practicality of the composite.

3.4 *Scanning Electron Microscopy (SEM) analysis*

The morphology of the fragmented specimens was investigated using a Hitachi SU3500 SEM working at 30 kV. The specimens were given a small layer of gold material to improve their conductivity and make SEM imaging easier (Vardhan *et al,* 2021). Through SEM examination, the surface appearance and structure of composite materials may be seen with great detail. We can learn more about the failure mechanism, the interaction between the fibres and the matrix, and the distribution of the reinforcing fibres throughout the composite matrix by looking at the fracture surfaces. SEM examination allows for a detailed evaluation of the composite microstructure and offers useful visual data. This study helps to understand the mechanical characteristics of the composite material and the effectiveness of the fiber-matrix interface, which adds to a thorough assessment of the material.

4. Results and Discussion

4.1. Density and void fractions

Table 3 displays the density and void fraction findings for the composites. These factors are essential for deciding whether composites are appropriate for industrial applications, particularly when considering the desired characteristics of lightweight, ecologically benign, and mechanically robust materials. When basalt fibres are mixed with jute fibres, the theoretical density of the composites varies. The density of the composite rises as the proportion of jute fibres does as well. This is due to the higher density of jute fibres compared to other fibres. The experimental results, which show that the composite density increases as the jute fibre content rises, are consistent with this tendency. Notably, composites' real density is only slightly higher than their theoretical density. This is because trapped gases were introduced during the manual lay-up production process (Muralidharan *et al,* 2022).

Table 3. Density and void fractions

Sample	Theoretical density (g/cm^3)	Actual density (g/cm^3)	% Volume fraction of voids
L1	1.298	1.239	4.54
L2	1.325	1.265	4.52
L3	1.353	1.301	3.84
L4	1.338	1.278	4.32

4.2. Tensile test

The tensile test results offer important information on the effectiveness of composites under varied moisture conditions. The effects of water absorption on the tensile strength and tensile modulus of composites are shown in Figures 4 and 5. Untreated fibers significantly lose 33% of their tensile strength when they are exposed to moisture. This suggests that the mechanical properties of the composites are adversely affected by moisture absorption. When alkali-treated composites are tested, the drop in tensile strength is, however, reduced to 22%. This improvement results from treating fibers with alkali, which lowers their ability to absorb moisture and raises their resistance to moisture (Fiore, *et al,* 2015). The tensile properties of the composites are further impacted by the hybridization of jute and basalt fibers. Figure 4 shows that the addition of jute fibers caused a drop in tensile values ranging from 17% to 18%. L3 turned out to be the most efficient hybrid combination out of all those considered. In comparison to other compositions, this combination shows higher tensile performance. The interactions between the two fiber types are to blame for the improved tensile qualities, which lead to a tension-resistant structure with reinforced tensile properties. It's interesting to note that jute fibers' increased hydrophobicity, which is caused by their higher moisture content, may be a factor in their poorer overall compositional qualities. But the ideal hybrid composition successfully strikes a compromise between the benefits of basalt fibers and the moisture resistance acquired through alkali treatment. These findings highlight the importance of fiber treatment and hybridization in enhancing the tensile capabilities of composites, especially in humid settings. The tensile strength and moisture resistance of composites may be increased by using the right fiber treatments and making careful hybrid composition choices, making them suited for applications demanding lightweight, ecologically friendly, and mechanically strong materials.

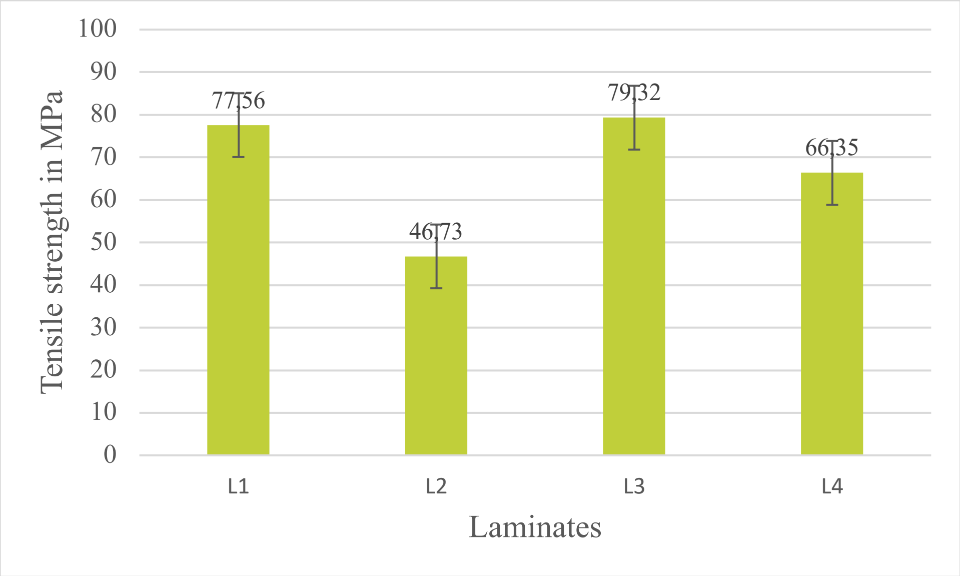

Figure 4: Tensile strength of various composites

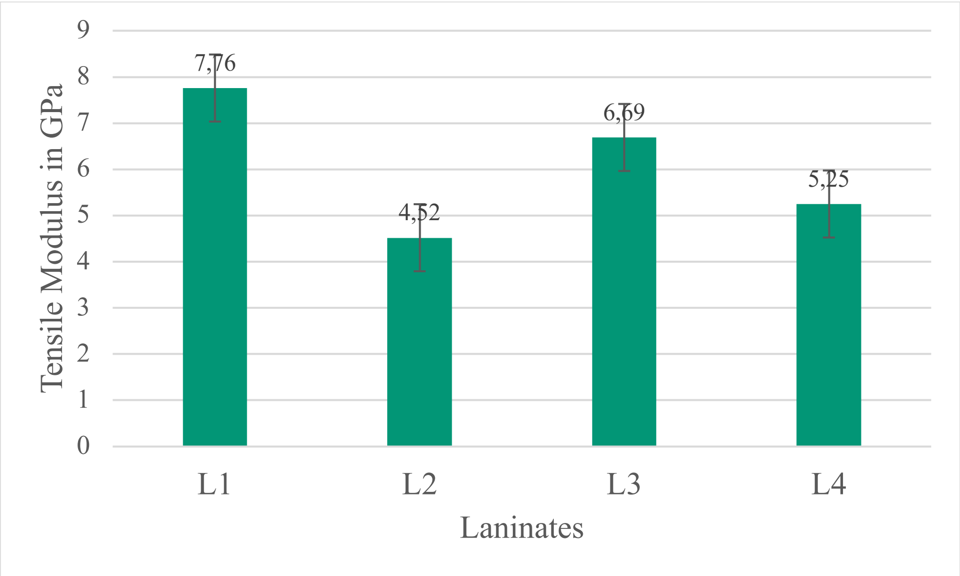

Figure 5. Tensile modulus of various composites

4.3 Flexural Test

The flexural strength and flexural modulus of the composites in dry and water-absorbent circumstances are usefully shown by the flexural test results presented in Figures 6 and 7. These discoveries provide insight into how composite materials respond to bending stresses and how moisture affects their mechanical characteristics. Examining the dry samples reveals that the flexural strength rises proportionately with the addition of jute fibers. A number of things contributed to this improvement. First, the inclusion of jute fibers enables a better load transfer to the fibers, increasing the total strength of the composites. Additionally, the better adhesion at the Fibers and matrix contact adds to the increased flexural strength. Additionally, the cellulose fibers in the composites contribute to the flexural characteristics by supporting bending forces in addition to the jute fibers. The findings do, however, show that water absorption reduces the flexural strength of composites. Water absorption reduces flexural strength by 46% without alkali treatment. However, the loss in flexural strength is just 28% when composites are alkali-treated.

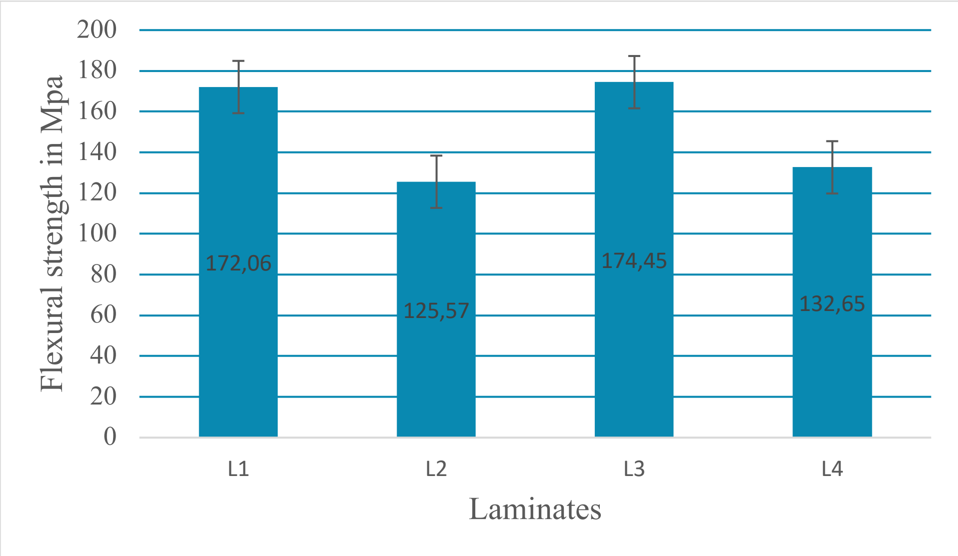

Figure 6. Flexural strength of various composites

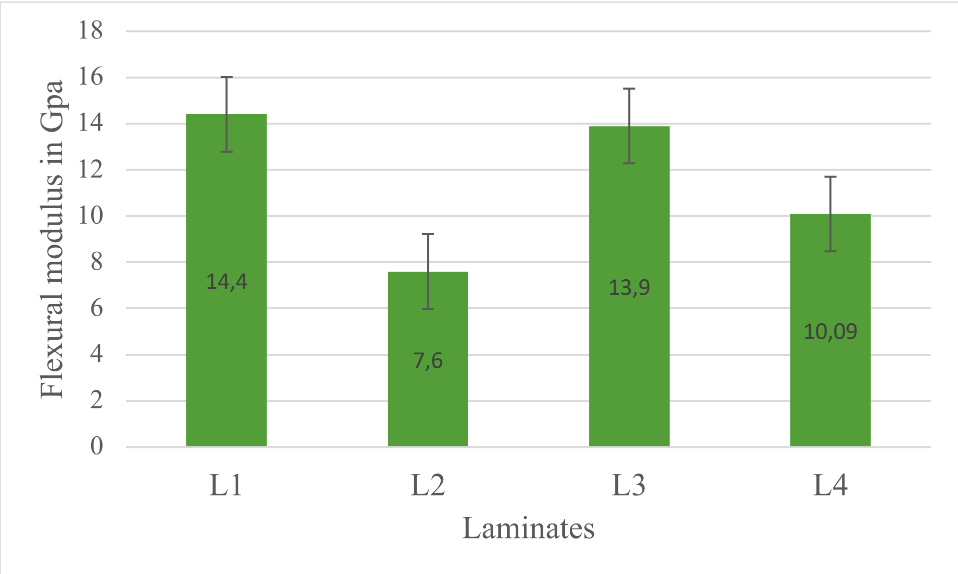

Figure 7. Flexural Modulus of various composites

The capacity of the alkali treatment to decrease moisture absorption and raise the fibers' resistance to moisture is what leads to this improvement. Additionally, the negative impact of water absorption on flexural strength may be further reduced by using hybrid compositions. With a 17% to 24% drop in flexural strength, the composition with two outer layers of basalt and two inside layers of jute fibers shows the best results. This shows that fiber hybridization offers more benefits in terms of total flexural performance and moisture resistance. The entry of water molecules into the fiber-matrix interface is the likely cause of the reduced flexural strength seen under damp environments. As a consequence, the fibers grow and gaps develop between them and the matrix, which eventually leads to fiber separation. The breakdown of fibers brought on by moisture also causes the separation of fibers into fibrils, which lowers the flexural strength of damp hybrid composites. The relevance of moisture resistance in achieving the best flexural characteristics for composites is shown by these findings. For improving the composites' resistance to moisture absorption and reducing the negative effects on flexural strength, alkali treatment and the choice of hybrid compositions are crucial (Calheiros *et al.,* 2013). Because of this, composites may be used in applications that require for lightweight, ecologically friendly, and mechanically durable materials even in areas with a lot of moisture.

4.4 Impact Test

The impact test findings shed insight on the hybrid composites' impact strength in both dry and wet circumstances, as shown in Figure 8. It is clear that composites' impact strength is much lower in wet than in dry circumstances. This is explained by the development of more micro cracks when water molecules diffuse into the area where the fibers and matrix come into contact. As a result, the connection between the fibers and the matrix deteriorates, lowering impact strength. Further investigation demonstrates that compared to dry composites, water absorption lowers the impact strength of composites containing 15% basalt fibers by 25%. Nevertheless, this decrease may be lowered to a range of 12% to 15% by using the hybridization technique.

Notably, compared to other compositions, the hybrid composition made up of the L3 combination shows greater impact resistance. These results highlight the importance of moisture resistance in preserving the ideal impact strength of composites. The fiber-matrix interaction is jeopardized.

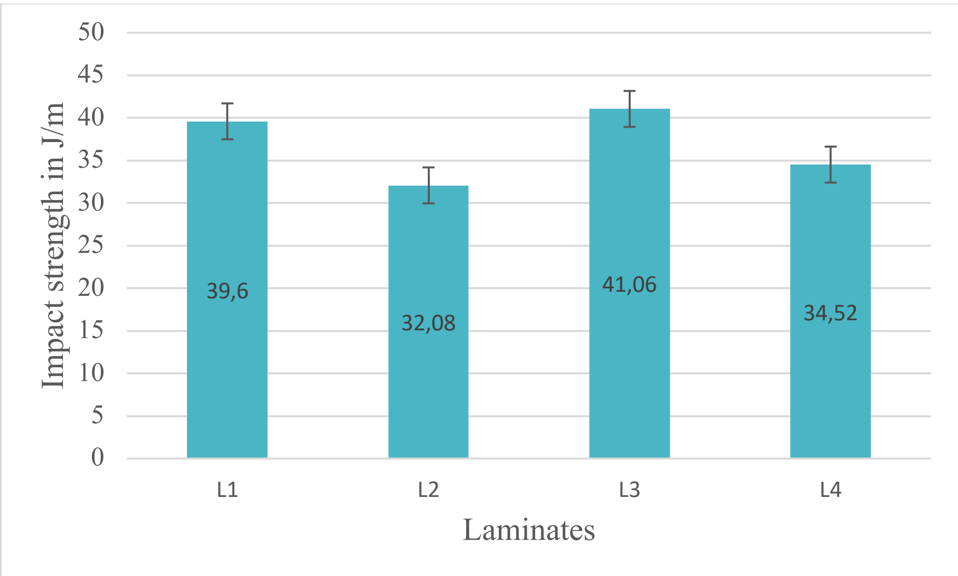

Figure 8. Impact strength of various composites

When water molecules diffuse into the contact zone and cause the creation of micro cracks. As a result, damp hybrid composites have less impact resistance. Jute fibers with the right hybrid composition, however, may be used to successfully reduce the detrimental effects of water absorption on impact strength (Saaidia *et al,* 2023; makhlouf *et al,* 2022; Sakhti Balan *et al,* 2020). These discoveries have important ramifications for companies looking to develop lightweight, ecologically benign, and mechanically durable materials. Composites may keep their impact strength even in areas with high amounts of moisture by thinking about the hybridization of fibers and using moisture-resistant methods, including alkali treatment (Doddamani *et al,* 2012). This guarantees their appropriateness for uses in which impact resistance is essential and aids in the development of lightweight and robust materials in a number of sectors.

4.5 Moisture Absorption test

Lignocellulosic fibers, which are often employed in natural fiber-reinforced composites, have a tendency to absorb moisture, leading to dimensional instability and modifications in mechanical characteristics. Knowing how natural fiber composites absorb water is crucial to figuring out how long they will last in a given application. Water molecules enter these composites via micro-gaps between polymer chains, capillary action inside the fiber-matrix interstitial spaces, and flaws at the fiber-matrix interfaces. The interface between the fiber and matrix, as well as the fiber itself, via hydrogen bonding, are the main sites of moisture absorption (Moudood *et al,* 2019; Lotfi *et al,* 2021). Table 3 shows the hybrid composites created for the study's water absorption findings. The findings show that hybridization significantly affects the water absorption of the composites. This is because the fiber's external surface has been hydroxide-treated, increasing its water resistance. In comparison to the other compositions, L3 (BJJB) has the greatest resistance to water absorption. Additionally, the results show that fibers begin to significantly increase weight after 1 day of immersion and begin to absorb the most water after that. After this, differences in water absorption are seen, as seen in Table 3. Long-term immersion in water demonstrates that water absorption approaches a saturation point, suggesting that the fibers' maximum ability to absorb moisture has been reached. Following a 5-day immersion period, saturation behavior is seen. With L3's improved composition, the reduced water absorption in hybrid composites shows it's potential for usage in situations where moisture resistance is crucial. These composites have improved dimensional stability and durability due to the alkali-treated fibers' capacity to prevent water infiltration, making them suited for businesses looking for lightweight, environmentally friendly, and mechanically robust materials.

Table 3: Water absorption of hybrid composites

Moisture Absorption in days	**% Water absorption**			
	L1	**L2**	**L3**	**L4**
1	2.486	3.105	5.744	4.434
2	3.120	3.398	5.451	4.462
3	3.120	3.398	5.744	4.479
4	3.945	3.692	5.865	4.481
5	4.219	4.571	6.038	4.50

4.6 Scanning Electronics Microscopy

SEM enables a detailed analysis of the morphology of fibre surfaces. Composites made of polyester-hybrid natural fibres can efficiently be cleaned of contaminants and have their hydrophilicity reduced using chemical treatments. The surface morphology of treated and untreated polyester natural fibre composites was compared using SEM analysis. Untreated fiber-reinforced composites display more widespread fibre breakdown than their alkali-treated counterparts. The fracture surface of dried, untreated hybrid fibres is shown in Figures 9A which also shows weak fibre-matrix adhesion and crack formation during tensile fracture. As illustrated in Figure 9B, alkali treatment on the other hand causes the surface of the fibres to become coarser, improving the contact between the matrix and fibres. When utilised in the Creation of composites, chemical treatments increase surface porosity and roughness, which enhances the mechanical interlocking adhesion between fibres and the matrix. Wet hybrid composites exhibit a smaller range of mechanical characteristics than their dry equivalents. When composite specimens are submerged in water, hydrogen bonds between the water molecules and the cellulose begin to form, which is what causes this behaviour. The interfacial bonding and tensile characteristics of composite specimens are decreased as a result of the penetration of water molecules into the fiber-matrix region. The fiber-matrix adhesion is also weakened as a result of fibre expansion, which also causes fibre separation from the matrix Figure 9C. The fracture surfaces of hybrid basalt and jute composites are significantly better understood thanks to the SEM study. The difference between treated and untreated, dried composites shows how important alkali treatment is for improving the interface and overall mechanical performance. Additionally, research on wet composites demonstrates how water absorption negatively affects interfacial adhesion and mechanical performance (Hasan *et al,* 2022). These discoveries promote the development of lightweight, environmentally friendly, and mechanically robust materials for a range of industrial applications and help to understand the microstructural changes that take place in composites.

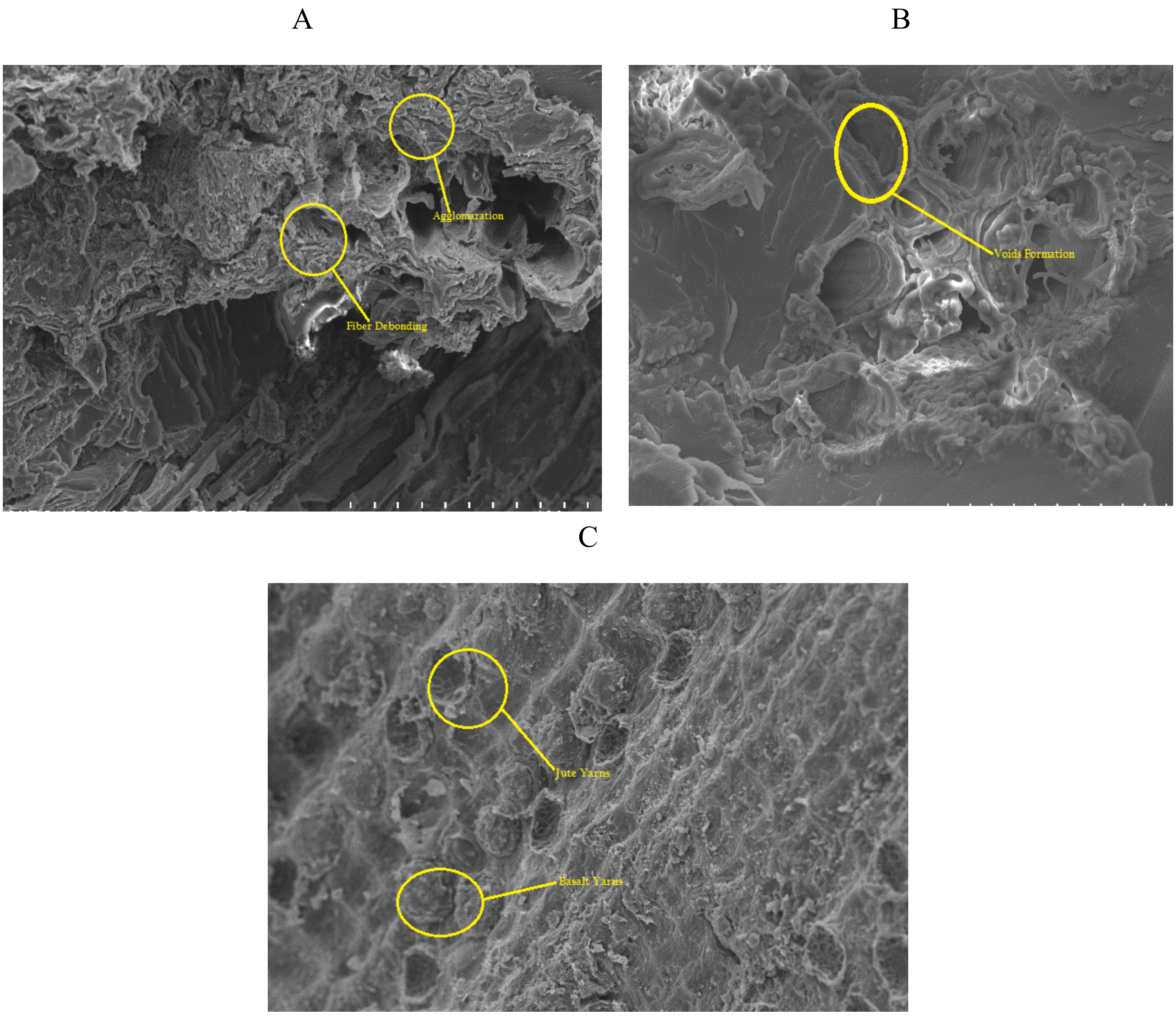

Figure 9. A. Basalt composite B. Jute Composite C. Hybrid composites

Conclusion

The characteristics of basalt and jute fiber-based hybrid composites were examined in this paper. Several characterization techniques were used to examine the composites' density, void fraction, tensile strength, flexural strength, impact strength, and water absorption. The most significant findings are as follows:

- Jute fibres added to the composite made it denser, however the actual density was a little bit less than the predicted density because of trapped gases during manufacture. The hybrid composition of L3 had the lowest void fraction out of all the fibre compositions studied.
- The tensile strength of the composites was impacted by water absorption. Untreated fibres drastically lost tensile strength when exposed to water. However, basalt and jute fibres were hybridised, which furthered the improvement, and alkali treatment of the fibres decreased this loss. The hydrophilicity of the banana fibre and its impact on the moisture content are most likely to blame for the composition of L3 hybrid composite producing the greatest outcomes.
- The addition of jute fibres enhanced the composites' flexural strength in dry conditions. This improvement can be attributed to elements like enhanced adhesion at the fiber-matrix interface, increased load transmission to the fibres, and the ability of cellulose fibres to withstand bending loads. Water absorption caused a reduction in flexural strength, however alkali treatment and hybridization counteracted this effect. The material had a superior flexural strength because to its two basalt outer layers and two jute inside layers.
- Due to water molecules accessing the fiber-matrix interface and creating micro cracks there, composites' impact strength was lower in wet settings than it was in dry conditions. Water absorption was less of an issue due to the hybridization method. Comparatively speaking, the composition made out of BJJB composites demonstrated higher impact resistance.
- Moisture absorption alters the dimensional stability and mechanical properties of composites made of basalt and jute Lignocellulosic fibres. Water molecules swelled and weakened interfacial adhesion at fibre-matrix micro-gaps and interfaces. Fibres treated with alkali became less porous to water, which decreased water absorption during hybridization. Water was least absorbed by L3 hybrid composite.
- A SEM analysis revealed the shape of the fibre surfaces as well as the effects of chemical alterations, fiber-matrix bonding, and water absorption. Alkali treatment enhanced the fiber-matrix interface, however water absorption weakened the link between the fibres and the matrix by causing swelling and separation of the fibres.

The hybrid composites, taken as a whole, showed promising characteristics, making them appropriate for applications requiring lightweight, environmentally benign, and mechanically durable materials. Jute fibre addition, alkali treatment, and fibre hybridization all enhanced composites' mechanical properties and water resistance. These results support the development of environmentally friendly composites for a range of industrial applications, especially those that emphasize the use of lightweight materials with improved durability.

Acknowledgement, the Authors are grateful to Department of Mechanical Engineering, Dr. Ambedkar Institute of Technology Bengaluru are acknowledged.

Disclosure statement: *Conflict of Interest:* The authors declare that there are no conflicts of interest.

Compliance with Ethical Standards: This article does not contain any studies involving human or animal subjects

References

Ad C., Benalia M., Djedid M., Elmsellem H., Ben Saffedine F., Messaoudi A., Kadmi Y., Ouzidan Y., Hammouti B. (2016). A new lignocellulosic material based on Luffa cylindrica for Nickel(II) adsorption in aqueous solution, *Mor. J. Chem.* 4(4), 1096-1105

Akartasse N., Azzaoui K., Mejdoubi E., Elansari L. L., Hammouti B., Siaj M., Jodeh S., Hanbali G., Hamed R., Rhazi L. (2022a) Chitosan-Hydroxyapatite Bio-Based Composite in film form: synthesis and application in Wastewater, *Polymers,* 14(20), 4265, https://doi.org/10.3390/polym14204265

Akartasse N., Azzaoui K., Mejdoubi E., Hammouti B., Elansari L.L., Abou-salama M., Aaddouz M., Sabbahi R., Rhazi L. and Siaj M. (2022b), Environmental-Friendly Adsorbent Composite Based on Hydroxyapatite/Hydroxypropyl Methyl-Cellulose for Removal of Cationic Dyes from an Aqueous Solution, *Polymers,* 14(11), 2147; https://doi.org/10.3390/polym14112147

Alsuwait R.B., Souiyah M., Momohjimoh I., Ganiyu S.A., Bakare, A.O. (2022). Recent Development in the Processing, Properties, and Applications of Epoxy-Based Natural Fiber Polymer Biocomposites. *Polymers*, 15(1), 145.

Balaji J., Nataraja M.M., Sadashiva K. (2023). Studies on Thermal Characterization of Hybrid Filler Polymer Composites with Rice Husk and Aluminium Nitride, *J. Mater. Environ. Sci.*, 14(4), 511-519.

Balaji J., Nataraja M.M., Vinod K.L., Sadashiva K. (2022). Experimental Investigation on Mechanical Properties of Epoxy with Hybrid Filler Composites. *Proceedings of Fourth International Conference on Inventive Material Science Applications. Advances in Sustainability Science and Technology*. Springer, Singapore. https://doi.org/10.1007/978-981-16-4321-7_57.

Calheiros F.C., Pfeifer C.S.C., Brandão L.L., Agra C.M., Ballester R.Y. (2013). Flexural properties of resin composites: influence of specimen dimensions and storage conditions. *Dental Materials Journal*, 32(2), 228-232.

Doddamani M.R. and Kulkarni S.M., (2012). Flexural behavior of functionally graded sandwich composite. Finite element analysis-*applications in mechanical engineering*, 131-154.

Elidrissi A., El barkany S., Amhamdi, H., Maaroufi A., Hammouti B. (2012), New approach to predict the solubility of polymers Application: Cellulose Acetate at various DS, prepared from Alfa "Stipa - tenassicima" of Eastern Morocco, *J. Mater. Environ. Sci.* 3 (2), 270-285

Fiore V., Di Bella, G. and Valenza, A. (2015). The effect of alkaline treatment on mechanical properties of kenaf fibers and their epoxy composites. *Composites Part B: Engineering*, 68, 14-21.

Fiore V, Calabrese L. (2019). Effect of stacking sequence and sodium bicarbonate treatment on quasi-static and dynamic mechanical properties of flax/jute epoxy-based composites. *Materials.* 12(9), 1363

Hasan A., Rabbi M.S. and Billah M.M. (2022). Making the Lignocellulosic fibers chemically compatible for composite: A comprehensive review. *Cleaner Materials*, p.100078.

Jain J., Sinha, S. and Jain, S., (2021). Compendious characterization of chemically treated natural fiber from pineapple leaves for reinforcement in polymer composites. *Journal of Natural Fibers,* 18(6), 845-856.

Khan F.M., Shah, A.H., Wang, S., Mehmood, S., Wang, J., Liu, W. and Xu, X., (2022). A comprehensive review on epoxy biocomposites based on natural fibers and bio-fillers: Challenges, recent developments and applications. *Advanced Fiber Materials*, 4(4), *683-704.*

Lakshmi Narayana S. & Gopalan V. (2023) Mechanical characterization of particle reinforced jute fiber composite and development of hybrid Grey-ANFIS predictive model, *Journal of Natural Fibers,* 20(1), 2167033, DOI: 10.1080/15440478.2023.2167033

Lotfi A., Li H., Dao D.V. and Prusty G. (2021). Natural fiber–reinforced composites: A review on material, manufacturing, and machinability. *Journal of Thermoplastic Composite Materials*, 34(2), 238-284.

Lv H., Yu H., Han J., Hou Y., Sun Y., Liu K., Zhou W., Chen J. (2024) Tunicate cellulose nanocrystals reinforced modified calcium sulfate bone cement with enhanced mechanical properties for bone repair, *Carbohydrate Polymers,* 323, 121380, ISSN 0144-8617, https://doi.org/10.1016/j.carbpol.2023.121380

Makhlouf A., Belaadi A., Boumaaza M., Mansouri L., Bourchak M., and Jawaid M. (2022). Water absorption behavior of jute fibers reinforced HDPE biocomposites: Prediction using RSM and ANN modeling. *Journal of Natural Fibers* 1–18. doi:10.1080/15440478.2022.2114976

Moudood A., Rahman A., Khanlou H.M., Hall W., Öchsner A. and Francucci G. (2019). Environmental effects on the durability and the mechanical performance of flax fiber/bio-epoxy composites. *Composites Part B: Engineering*, 171, 284-293.

Muktha, K. and Gowda, B.K. (2017). Investigation of water absorption and fire resistance of untreated banana fibre reinforced polyester composites. *Materials Today: Proceedings*, 4(8), 8307-8312.

Muralidharan, M., Sathishkumar, T.P., Rajini, N., Navaneethakrishan, P., Ismail, S.O., Senthilkumar, K., Siengchin, S., Mohammad, F. and Al-Lohedan, H.A. (2022). Ply-stacking effects on mechanical properties of Kevlar-29/banana woven mats reinforced epoxy hybrid composites. *Journal of Industrial Textiles*, 52, p.15280837221128024.

Saaidia A., Ahmed Belaadi A., Boumaaza M., Alshahrani H. & Bourchak M. (2023) Effect of Water Absorption on the Behavior of Jute and Sisal Fiber Biocomposites at Different Lengths: ANN and RSM Modeling, *Journal of Natural Fibers,* 20:1, DOI: 10.1080/15440478.2022.2140326

Sabarinathan P., Annamalai V., Rajkumar K., Vishal K. (2021). Effects of recovered brown alumina filler loading on mechanical, hygrothermal and thermal properties of glass fiber–reinforced epoxy polymer composite. *Polymers and Polymer Composites,* 29(9_suppl), S1092-S1102. doi:10.1177/09673911211046780

Sadashiva K., Purushothama K.M. (2022). Flexure and interlaminar shear properties of ramie/ silk fibre epoxy hybrid composite, *Materials Today: Proceedings*, 68, 2536-2540. doi.org/10.1016/j.matpr.2022.09.357.

Sadashiva K., Nataraja M. M, Balaji J., Kishan G. B, Preetham V., Nithin Teja B. M., Nitin N. (2023). Investigation on Mechanical Behavior of Bio Based Natural Hybrid Epoxy Composites". *Journal of Materials and Environmental Science*, 14(2), 246-254.

Sadashiva K, K.M. Purushothama., (2023), Investigation on Mechanical and Morphological Characteristics of Ramie/Silk with Epoxy Hybrid Composite of Filler OMMT Nanoclay, *Jordan Journal of Mechanical and Industrial Engineering*, 17 (2), 289-296.

Sadashiva K., Purushothama K.M. (2023), Physical and Mechanical Properties of Bio Based Natural Hybrid Composites, *Journal of Materials and Environmental Science*, 14(1), 131–140

Sakthi Balan G., Ravichandran M. (2020), Study of moisture absorption characteristics of jute fiber reinforced waste plastic filled polymer composite, *Materials Today: Proceedings,* 27, Part 2, 712-717, ISSN 2214-7853, https://doi.org/10.1016/j.matpr.2019.11.260

Sanjeevi S., Shanmugam V., Kumar S., Ganesan V., Sas G., Johnson D.J., Shanmugam M., Ayyanar A., Naresh K., Neisiany R.E. and Das O. (2021). Effects of water absorption on the mechanical properties of hybrid natural fibre/phenol formaldehyde composites. *Scientific Reports*, 11(1), 13385.

Sathishkumar T.P., Navaneethakrishnan P., Shankar S. and Rajasekar R. (2013). Characterization of new cellulose Sansevieria ehrenbergii fibers for polymer composites. *Composite Interfaces*, 20(8), 575-593.

Sekar S., Suresh Kumar S., Vigneshwaran S. and Velmurugan G. (2022). Evaluation of mechanical and water absorption behavior of natural fiber-reinforced hybrid biocomposites. *Journal of Natural Fibers*, 19(5), pp.1772-1782.

Vardhan D.H., Ramesh A. and Reddy B.C.M. (2021). Effect of ceramic fillers on flexural strength of the GFRP composite material. *Materials Today: Proceedings*, 37, 1739-1742.

(2023); http://www.jmaterenvironsci.com