ENHANCED THERMO-MECHANICAL PROPERTIES OF EPOXY COMPOSITES REINFORCED WITH WOVEN BASALT/JUTE AND METAL MESH LAYERS

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ABSTRACT:

The demand for high-performance hybrid composites that combine strength, sustainability, and thermal stability has led to the exploration of multi-material reinforcement strategies. This study investigates the mechanical and thermal behavior of epoxy-based polymer composites reinforced with an alternating sequence of woven basalt fibers, natural jute fibers, and embedded metallic mesh layers. The composite architecture is designed to synergize the high-temperature resistance of basalt, the eco-friendliness of jute, and the structural reinforcement provided by the metal mesh.

Composite laminates were fabricated using a hand lay-up method followed by compression molding, with varying layer sequences and stacking orders. Mechanical properties including tensile strength, flexural strength, and impact resistance were evaluated in accordance with ASTM standards. Thermal performance was assessed using thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) to determine degradation temperatures and thermal transitions.

The results revealed that the inclusion of metal mesh significantly enhanced the load-bearing capacity and rigidity of the composite, while woven basalt fibers contributed to improved thermal resistance. The presence of jute fibers added sustainability and weight reduction without severely compromising structural integrity. Among the tested configurations, the hybrid laminate with sequential layering of basalt, metal mesh, and jute demonstrated optimal balance between mechanical strength and thermal stability.

This study highlights the potential of strategically layered hybrid composites in applications demanding both structural robustness and thermal endurance, such as automotive panels, aerospace interiors, and thermal shields. The findings support further development of multi-scale reinforced natural fiber composites as a sustainable alternative to conventional materials.

1.INTRODUCTION

The growing need for sustainable and high-performance materials in structural and thermal applications has driven significant research into hybrid polymer composites. Traditionally, synthetic fiber-reinforced polymer composites such as glass or carbon fibers have dominated in sectors like aerospace, automotive, and construction due to their superior mechanical properties. However, environmental concerns, cost, and recyclability issues have prompted a shift toward natural fibers and hybrid reinforcement strategies that combine synthetic, metallic, and bio-based components.

Natural fibers like jute offer several advantages, including low density, renewability, biodegradability, and cost-effectiveness. However, their mechanical and thermal performance is typically inferior to that of synthetic fibers. On the other hand, basalt fibers, derived from volcanic rock, offer a promising middle ground—providing excellent thermal resistance and good mechanical properties, while still being environmentally benign compared to synthetic alternatives.

Integrating metallic mesh layers into fiber-reinforced composites has recently gained attention as a novel technique to enhance stiffness, impact resistance, and electrical/thermal conductivity. Metal meshes serve as structural skeletons, improving load distribution and damage tolerance, particularly under dynamic loading or thermal stress conditions. When strategically combined with woven natural and mineral fibers, such metal reinforcements can significantly improve the thermo-mechanical performance of composite laminates.

This research focuses on a sequentially woven hybrid composite made of alternating layers of jute and basalt fibers, interlaced with stainless steel mesh, and bound in an epoxy matrix. The objective is to evaluate how the layering sequence, material synergy, and metal mesh integration influence the mechanical strength and thermal stability of the composite. By assessing key performance indicators such as tensile and flexural strength, impact resistance, and thermal degradation behavior, the study aims to identify the optimal configuration for real-world structural and thermal applications.

The novelty of this work lies in the hybrid architecture that fuses natural, inorganic, and metallic materials into a single composite system. The findings have practical implications for industries seeking to reduce reliance on synthetic materials without compromising performance, especially in applications where heat resistance and mechanical integrity are critical.

2. MATERIALS AND METHODS

2.1 Woven stainless steel wire mesh, woven jute fabric, woven basalt fabric and epoxy resin

Vasavibala Resins, an Indian company, supplied the epoxy as a polymer matrix. Hardener and curing agent were used in a 1:10 ratio for the composite preparation. The jute and basalt fabrics used in this study were supplied by Gogreen Products-India. The jute fabric was 0.4 mm thick, while the basalt fabric was 0.26 mm thick. The warp orientation of the jute fabric was 90°, while the weft orientation of the basalt fabric was 0°. Jute fiber has a density of 1.4 g/cm3 and a ductile strength of 1034 MPa. The woven basalt material serves as a strong fibre. Developing interwoven composite composites required a robust damping reinforcing material, and jute fibre provided this. Basalt fibre has the density of 2.7 g/cm3 and a tensile strength of 4750 MPa. Jute and basalt fibre were subjected to alkaline and acetylene surface modification treatments to increase matrix-reinforcement adhesion.

2.2 Manufacturing of layered jute composites with the influence of basalt fiber placement

Using VARTM process, a laminate composed of steel wire mesh, jute, basalt, and epoxy was created, which is considered the most promising method. A compression load of 10 MPa was continued throughout the procedure. After being subjected to direct sunshine for 24 hours, the composites were treated in a heater for 60 minutes around 70°C. The dissimilar woven layering configurations (WLA-I, WLA-II, WLA-III, and WLA-IV) used in the composites and entangled composites produced are depicted in Figure 1. Weight fractions of the matrix and fiber for the woven layering arrangement composites are listed in Table 1. The fiber arrangements used in the composites were identified as woven wire mesh (W), woven basalt fiber (B), and woven jute fiber (J).

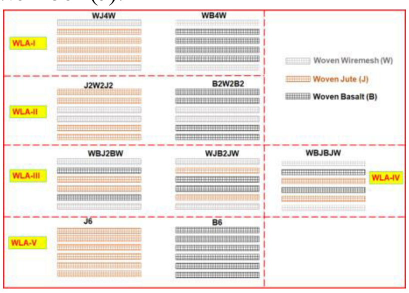

Figure 1: Jute fiber location and layer arrangement of composites

2.3 Experimentation of flexural and tensile

ASTM D638 standard was followed to create dog bone-shaped tensile specimens. The specimens were then subjected to tensile testing making use of a Universal Testing Machine (UTM) containing two grips. The specimen was positioned between both grips and the stretchable side was moved at a steady velocity of 5 mm/min. The strength and stiffness of the generated composites were tested using the ASTM D790 standard. For this aim, a three-point bending testing was coupled to the same UTM. Standard and broken characteristic flexural and tensile test samples are shown in Figure 2 (a-c) and 3 (a-c). The five specimens were tested and a standard deviation was reported for each testing condition.

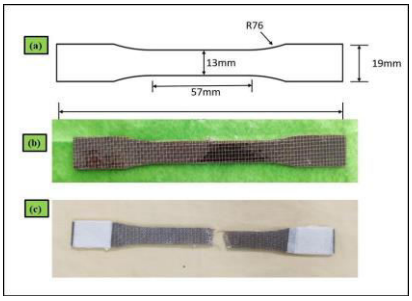

Figure 2 (a) Standard size tensile specimen, (b) Tensile WBJBJW composite specimen, and (c) Tensile cracked WBJBJW composite

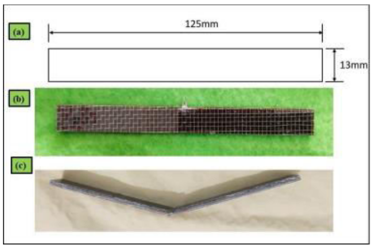

Figure 3 (a) Standard size flexural specimen, (b) Specimen for flexural WBJBJW composite, and (c) Specimen for flexural fractured WBJBJW composite

2.4 Thermogravimetric analysis

The researchers utilized TGA-SDT 2960 apparatus that combines DSC-TGA to assess thermal properties of basalt and jute fibers, as well as their epoxy composites. The study's sample group was 10 mg, and thermal degradation was investigated in a nitrogen environment at a continuous temperature increase of 10°C/min in the temperatures range of 30 to 600°C. TGA method was employed in a controlled setting to measure weight loss at dissimilar temperatures and to identify the dilapidation temperatures of woven layering arrangement composites.

3. RESULTS AND DISCUSSION

3.1 Woven layered laminate flexural and tensile analysis

Figure 4 illustrates impact of various stacking configurations of natural basalt interlaced jute fiber composites on their tensile modulus and strength (WLA-I, WLA-II, WLA-III, and WLA-IV).

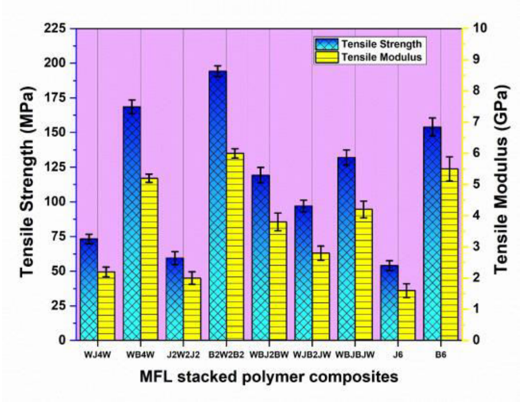

Figure 4 Mechanical properties Modification Of Jute Fiber Location In Polymer Composites

WLA-V control samples revealed that the clean basalt B6 composite had higher modulus and tensile strength than the J6 (jute fiber) composite, owing to the fact that basalt fiber is tougher than jute fiber. The ultimate tensile and elasticity of the WLA-I fabric layer layering configuration composites are significantly influenced by the position and number of fabric layers. The WB4W composite's woven layered layering arrangement had a greater tensile strength than the skin wire mesh with core jute fabric composite (WJ4W). Also, the inclusion of high-strength basalt fiber layers altered the tensile properties of the WB4W composites. In the WB4W woven layering design, the tensile strength was high and demonstrated a 111% increase over the WJ4W layering arrangement composite. In the WLA-II design, the skin/outer woven material layers determined the ductile strength and modulus, where B2W2B2 composite had better tensile strength than J2W2J2. The interlaced layering structure arranged alternately in the WLA-III interwoven laminates, and WBJ2BW design had higher tensile strength than WJB2JW stacking composites. The study consequence is reliable with the research conducted by Srinivasan et al. [22] where the jute-banana natural fiber mixed with epoxy mixtures using an exterior skin layer, E-glass fiber is used and demonstrated greater tensile strength than other stacking multilayer composites.

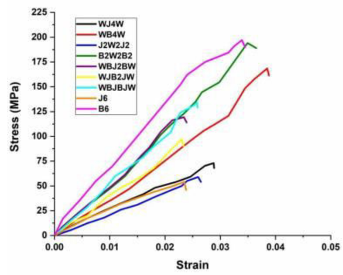

Figure 5 Stress-strain curvature of MFL composites

Figure 5 illustrates the stress-strain behaviour of WLA composites with various stacking arrangements, which were tested to contrast the effects having both great and low strength fiber placements on the test samples. Figure 5 displays the B2W2B2 merged had the highest toughness compared to all other WLA composites because of the strong interfacial adherence between the skin basalt fiber as well as the matrix, whereas B2W2B2 composite had higher elongation than the J2W2J2 layering arrangement laminate. Toughness of the WLA composites among pure basalt and jute composites determined tensile curves of woven layered layering arrangement composites. Additionally, as more basalt layers were added, the elongation to break decreased even though basalt fiber grows brittleness of the composites to some extent. The WBJ2BW woven layered layering arrangement composite had a higher strain than the WJB2JW. The rigidity of the WLA composites was also affected by the outer layer fiber's strength and toughness of the tensile curvature, as demonstrated in the research of Ramesh et al. [23], who found that glass fibers are employed in the laminate's outer layers, the tensile strength increases.

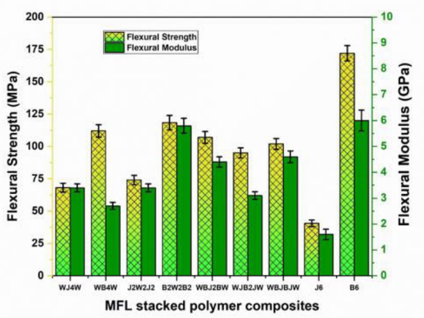

Figure 6 Flexural strength variation of jute fiber location in polymer composites

The figure 6 illustrates different modulus of elasticity and stiffness values woven layering patterns (WLA-I, WLA-II, WLA-III, WLA-IV, and WLA-V) manufactured composites. B6 flexural strength and modulus values of the composite were greater than those of pure jute. (J6) and basalt (B6) composites (control samples), was due to the increased bending strength of basalt fiber. Various type of core layers affected the flexural strong point and modulus of the

WLA-I (WJ4W & WB4W) composites. In the WJ4W layering arrangement, the strain in the surface jute coating was quickly transported to the basalt layer core bundle, which limited bending weight. The WLA-II composites, particularly the B2W2B2 design, had stronger flexural strength associated with the J2W2J2 composite. Outermost layers of composites bending stress was retained, minimizing stress transmission to the core layers. This was consistent with the findings of Amico et al. [24]. The WLA-III composites (WBJ2BW and WJB2JW) flexural strength was impacted by a high-strength outer fiber and an alternative layer. The experimental results demonstrated that the addition and placement of a substantial number of basalt layers interlaced with epoxy composites improved their mechanical properties.

3.2 Fracture Surface Analysis

The images in Figure 7 (a-f) display the cracked surfaces of the composite tensile samples that were loaded. These specimens consisted of uncontaminated basalt, pure jute, and mixture composites, which exhibited various types of fiber failure, including fiber breakage, pullout, splitting, and debonding from the epoxy matrix. The WB4W composite, shown in Figure 7 (c), demonstrated fiber splitting in both transverse and longitudinal orientations. In contrast, frail attachment interaction amongst the fiber and matrix resin in the WJ4W composite, leading to fiber pullout and void formation, as seen in Figure 8 a. B2W2B2 and B2W4B2 had similar failure characteristics, including fiber breaking, as illustrated in Figure 8 d. In addition, fiber breaking was discovered in a direction perpendicular of the WBJ2BW composite, as revealed in Figure 8 b. The results are reliable with previous research on hybrid natural polymer fiber composites surface fracture by Fiore et al. [15].

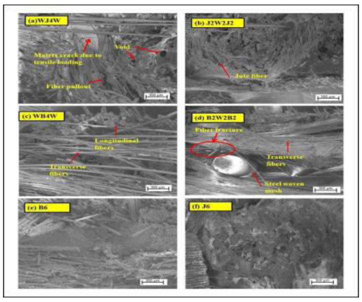

Figure 7 Typical tensile fracture SEM images of WLA composites

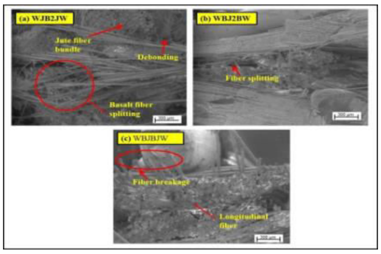

Figure 8 Typical tensile fracture SEM images basalt/jute/ wire mesh composites

3.3 Thermo gravimetric analysis

The figure 9 illustrates TGA curvatures of various interlaced composites. The use of wire mesh interwoven with jute and basalt composites in both skin and core layers significantly affects their thermal possessions. In addition of basalt fiber to composites enhances their thermal stability, pushing the start and terminal degradation temperatures to higher ranges the quantity of basalt fiber layers grows. The TGA curves designate three stages of weight loss: preliminary mass loss (about 5%), considerable mass loss (80%), and ultimate mass loss near the final of the degradation curvatures. Table 2 shows the stating and highest mass loss temperatures for different woven layering arrangement composites. The starting mass loss in these composites is mainly due to moisture removal from the jute fiber, while the additional stage of mass loss is caused by epoxy volatilization and fiber breakdown. The final weight loss is due to residue loss, matrix, and fiber degradation. Pure basalt composite exhibits very little weight loss as it has greater thermal stability than jute fiber, even at high temperatures.

The skin basalt layers in WLA composites significantly increases thermal resistance. The composites of B6 and B2W2B2 have higher thermal stability than earlier woven layered arrangement composites. Pure basalt layered composites exhibit the highest thermal resistance (462°C) among the interlaced composites. Alternating basalt coatings limiting temperature flow to jute coatings could be the reason for this temperature resistance in hybrid mixtures.

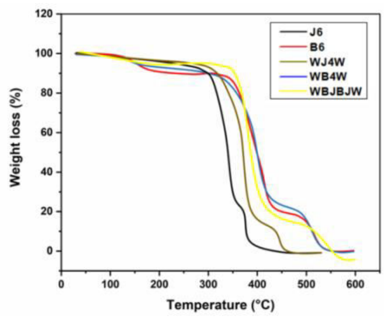

Figure 9 Thermal characteristics of MFL layered composites

Table 2 Thermal examination of WLA-I, WLA-II, WLA-III, WLA-IV & WLA-V composites

Explanation	Categories of composites	Degradation temperature (°C)	
		Initial degradation	Major degradation
WLA-I	WJ4W	282	340
	WB4W	326	392
WLA-II	J2W2J2	278	328
	B2W2B2	330	408
WLA-III	WBJ2BW	315	380
	WJB2JW	308	359
WLA-IV			
	WBJBJW	320	364
WLA-V	J6	275	334
	B6	342	462

4. CONCLUSIONS

This study has successfully explored the thermo-mechanical behavior of a novel hybrid composite consisting of woven basalt and jute fibers interlaced with metallic mesh layers within an epoxy matrix. The results clearly demonstrate that the strategic layering of these materials offers a synergistic improvement in both mechanical and thermal properties.

The inclusion of basalt fibers contributed significantly to the thermal resistance and structural integrity of the composite, while jute fibers added sustainability and reduced the overall weight. The integration of metal mesh played a crucial role in enhancing load-bearing capacity, stiffness, and impact resistance, acting as a reinforcing skeleton within the composite structure. Among the different stacking sequences examined, those incorporating alternating metal and fiber layers exhibited the most balanced performance.

From a thermal standpoint, the hybrid laminates showed increased degradation temperatures and improved thermal stability, which are essential for applications involving high operational temperatures or heat exposure. Mechanically, the composites with embedded metal mesh and basalt fibers outperformed those without, validating the effectiveness of the hybridization approach.

In conclusion, this work highlights the viability of using a multi-material reinforcement strategy to develop composites that are not only mechanically robust and thermally stable but also environmentally conscious. Such hybrid composites are well-suited for advanced engineering applications in automotive, aerospace, building materials, and thermal insulation systems, where durability and sustainability must go hand in hand.

Future research may expand on this foundation by exploring alternative fiber orientations, nanofiller enhancements, or real-time fatigue and thermal cycling tests to further optimize the performance and application range of these hybrid composites.

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