Research Article

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Evaluation of Impact Resistance and Interlaminar Shear Strength in Hybrid Composites of Kevlar, Hemp, and Carbon Fibers for Structural Applications

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ABSTRACT

The hybrid composites made using both synthetic and natural fibers are an ecofriendly alternative to conventional construction materials. This paper investigates the effect of hybridization of Kevlar, hemp and carbon fibers in the matrix of epoxy on impact resistance and interlaminar shear strength (ILSS). The composites were fabricated using the hand layup technique. Then, they were tested and evaluated for interlayer bonding contribution to resist shear stress. The results demonstrate that the impact resistance values (12.5 J and 15.8 J for 3 mm and 5 mm specimens, respectively), and ILSS values (6.8 MPa and 8.4 MPa) are superior on comparing with other materials (asbestos, cement and galvanised iron). The lightweight design and ecological advantages also make the composites well suited for use in roofing, cladding and protective structures.

Keywords: Hybrid composites; Kevlar; Interlaminar shear strength; Hand layup.

1. INTRODUCTION

Modern engineering relies heavily on composite materials, which possess a variety of properties, including but not limited to: high strength-to-weight ratio, corrosion resistance, and design flexibility. These materials are used quite extensively across construction, automotive and aerospace industries, where their many mechanical properties have performance advantages to conventional materials. Hybrid composites, comprising both synthetic fibers and natural fibers, have attracted interest since they offer a sustainable solution with reasonable mechanical properties. With respect to structural applications, impact resistance and inter-laminar shear strength (ILSS) are two critical properties, that characterize a material's resistance to sudden forces and internal bonding strength (Gangadhara, 2021).

1.1 Importance of Impact and ILSS Properties in Structural Applications

Impact resistance is an important property for materials used in dynamic loading environments such as roofing and cladding systems likely to be damaged by hail, debris, etc. Impact resistance and ILSS are particularly relevant for composite materials, as they determine the layer bonding resistance to shear stress in the material. Delamination is the peeling or separation of materials from each other at the laminate level. A material that exhibits high ILSS is less prone to delamination, ensuring structural stability of the material over a period. However, there is limited research related to assessment of these properties in hybrid composites for construction purposes.

1.2 Hybrid Composites

Hybrid composite materials are built by integrating multiple fibers with different properties in a single matrix system to impart specific mechanical properties (Veeranjaneyulu *et al*. 2023). Kevlar shows outstanding impact resistance allowing it to disperse dynamic loads across its surface and absorbing force effectively. Fig. 1 shows the fabric created out of Kevlar. Hemp is a natural fiber that is environmentally sustainable and contributes enough stiffness and toughness (Sangilimuthukumar *et al*. 2023). Hemp fabric is shown in Fig. 2. Carbon fiber has an impressive high stiffness and strength properties which significantly enhance ILSS. Fig. 3 shows carbon fiber fabric. The current study utilized Kevlar, hemp, and carbon fibers because of their complementary properties. The purpose of adding these three manmade fibers to the hybrid composite was to improve impact resistance or inter-laminar shear strength.

1.3 Epoxy Resin: A Robust Matrix Material

Composite materials are known to have a matrix material, which holds them together and enables load transfer. This study selected the Araldite LY 556/Aradur HY 951 system, an epoxy resin, known for its strong adhesion, excellent mechanical properties, and resistance to environmental degradation.

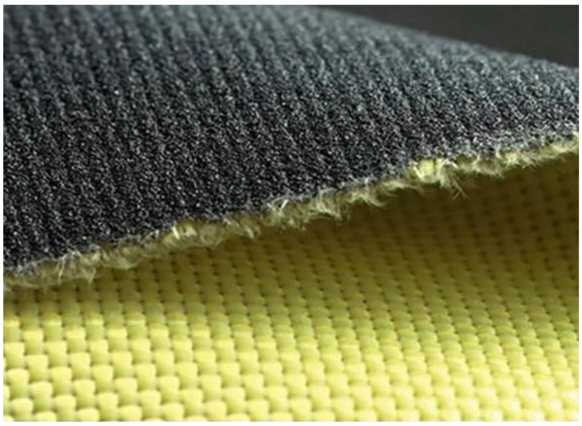

Fig. 1: Kevlar fabric

Fig. 2: Hemp fabric (Katrien *et al.* 2020)

Fig. 3: Carbon fabric

Due to the high bonding strength of the epoxy resin, the ILSS of the composite is increased, and the toughness of the resin improves the impact resistance of the composite (Karthik *et al*. 2022).

1.4 Fabrication Method: Hand Layup Technique

The composite panels were fabricated using hand layup technique for its simplicity and cost-effectiveness. This approach offers the ability to finely adjust laminate thickness and fiber orientation, both of which have significant effects on ILSS and impact properties. Although labor intensive, the hand layup method is suitable for producing high quality composite panels with specific performance requirements. Fig.4 shows the hand layup technique.

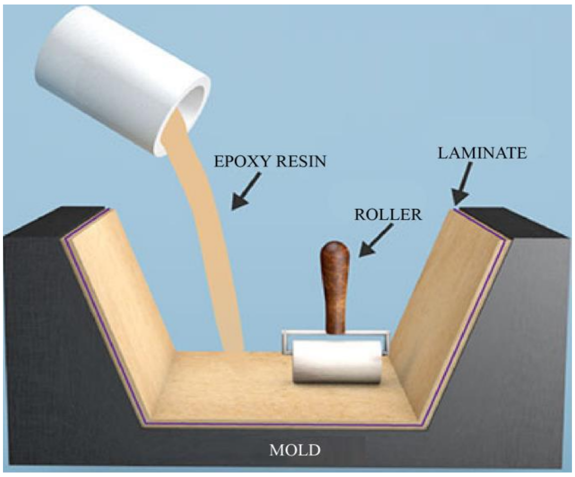

Fig. 4: Schematic of hand layup process (Wet lay-up/Hand lay-up manufacturing process for composites)

1.5 Brief Background

Recent studies reported on hybrid composite roof panels comprising Kevlar, hemp and carbon fiber as fibers, and epoxy resin as matrix demonstrated positive results. These natural and synthetic hybrid fibers can enhance the mechanical properties of the roof panels such as tensile and flexural strength (Negi *et al.* 2019). Natural fibers enhance the natural frequency of the hybrid composite. This combination of Kevlar and hemp has shown better results than other combinations (Anand *et al.* 2022).

Hemp-Kevlar-Carbon hybrid composites demonstrated superior mechanical properties, with hemp enhancing tensile strength, impact resistance, and hardness (Negi *et al*. 2019). Kevlar-Abaca composites exhibited the highest load-carrying capacity in tensile, flexural, and impact tests (Anand *et al*. 2022). Carbon nanotubes improved the performance of hemp/vinyl ester/carbon fiber composites. Alkaline treatment of hemp fibers enhanced mechanical properties in hemp-carbon hybrids (Ramesh *et al.* 2019). Kevlar-149-carbon fiber composites showed promising low-velocity impact resistance for aircraft applications (Ashik *et al*. 2021). The addition of bio-fillers like palm and coconut shell improved shock resistance in Hemp-Kevlar composites

(Jani *et al.* 2019). Overall, these studies highlight the potential of hybrid composites to combine the advantages of natural and synthetic fibers for various applications. Similar works are available in the literature (Gondi and Madhusudhana, 2020; Madhusudhana *et al*. 2019; Gondi and Jayakiran, 2024).

1.6 Research Gap and Problem Statement

Although traditional roofing materials like asbestos, cement, and galvanised iron (GI) are the most commonly used, they have some limitations. Asbestos is harmful to health, cement is not very strong, and GI corrodes with time. So, hybrid composites can be the suitable alternative, however, the ILSS and impact properties have not been fully studied regarding construction applications. To fill this gap, the present work investigates these properties in a hybrid composite of Kevlar, Hemp and Carbon fibres embedded in an epoxy matrix to assess its viability for structural applications.

1.7 Objectives of the Study

This study mainly focuses on the impact resistance and ILSS of a hybrid composite, which was developed from Kevlar, Hemp and Carbon fibers. It also intends to compare these properties with the properties of conventional roofing materials such as galvanized iron (GI), asbestos and cement. Additionally, this study aims to evaluate the practicality of implementing the composite in actual applications that require high resistance to impact and robust interlaminar bonding strength.

1.8 Novelty and Comparison with Existing Research

In this paper, a new hybrid composite is proposed with the impact resistance of Kevlar fibers, the sustainability of Hemp fibers and the rigidity of Carbon fibers. Although, previous works have studied specific properties such as tensile and flexural strength in hybrid composites, not many have studied the combined evaluation of impact resistance and ILSS. For example, Kevlar composites were showcased to have good impact resistance but also noted their high cost. Most of the research on composites from hemp have highlighted the environmental advantages of hemp composites but reported issues with their mechanical strength. Similarly, carbon fiber composites are known for their superior stiffness and ILSS, but they are less sustainable and more expensive. This work aims to achieve a compromise between performance and sustainability by combining these fibres into a single matrix composite. These results will benefit the wide use of hybrid composites in applications where both impact resistance and ILSS are critical.

2. MATERIALS AND METHODS

2.1 Materials

2.1.1 Reinforcements

Composite Reinforcements used in this study are Kevlar, hemp, and carbon fibers. The selection of Kevlar is to obtain superior impact resistance and tensile strength to guarantee the composite to resist the dynamic loads. Hemp's environmental sustainability made it an option, while its stiffness and toughness were suitable to strengthen other fibers. Carbon fiber was added for its exceptionally high stiffness-to-weight ratio, which, when combined with the enhanced ILSS, improves the overall mechanical properties of the composite.

2.1.2 Matrix Material

The matrix material used was an epoxy resin system (Araldite LY 556 with Aradur HY 951 hardener). To achieve the best curing and bonding properties, the ratio of resin to hardener was kept constant at 10:1 by weight.

2.2 Fabrication of Hybrid Composite Panels

2.2.1 Preparation of Materials

The fibers were divided into small pieces with uniform dimensions as required for each test specimen. The epoxy resin and hardener were mixed until a homogeneous mixture was achieved. Table 1 shows the properties and dimensions of the selected fabrics, while Table 2 summarizes their mechanical characterizations.

Table 1. Dimensions of fabrics

S. No.	Fabric name	Length (mm)	Width (mm)	Thickness (approx.)
1.	Hemp	1000	1000	0.50
2.	Carbon	1000	1000	0.30
3.	Kevlar	1000	1000	0.25

Table 2. Mechanical properties of fabrics

S. No	Property	Hemp	Carbon	Kevlar
1	Density (kg/m^3)	0.15	1600	1470
2	Young's Modulus (E) Gpa	80	250	125
3	Poisson's Ratio (μ)	0.25	0.3	0.35
4	Yield Strength (Mpa)	400	2000	3600
5	Tensile Strength (Mpa)	600	3500	4000
6	Thermal Conductivity (K) W/m^2	0.0045	5.7	0.05

2.2.2 Layup Process

The composite panels were fabricated using the hand layup technique. Initially, a release agent was applied to the mold surface to avoid sticking. Several layers of fibers were placed in the mold one after another, first Kevlar, then hemp, and carbon fibers were used. Each layer was fully saturated with the epoxy mixture to ensure a uniform and strong bond. The layup continued until the required thickness (3 mm or 5 mm) was obtained, then it was covered with release film and breathable felt, to remove excess resin and air bubbles.

2.2.3 Curing

The composite laminates were cured for 24 hours at room temperature under light pressure to remove potential contained air bubbles and ensure the right compaction. The poured panels were demolded after curing and were cut to appropriate dimensions. The front and back view of 3 mm and 5 mm thick cured composites is shown in Fig. 5 to 8, respectively.

Fig. 5: Front view of 5 mm-thick cured

Fig. 6: Back view of 5 mm-thick cured composite

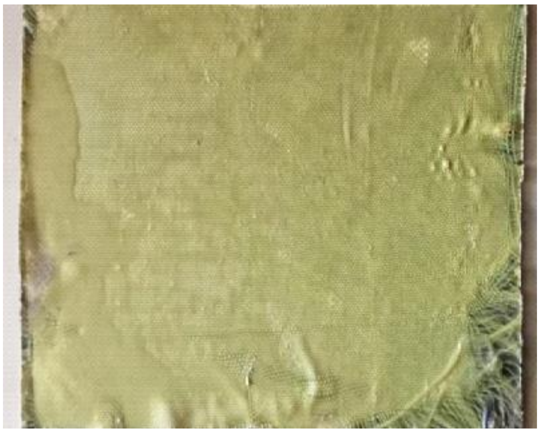

Fig. 7: Front view of 3 mm-thick cured

Fig. 8: Back view of 3 mm-thick cured

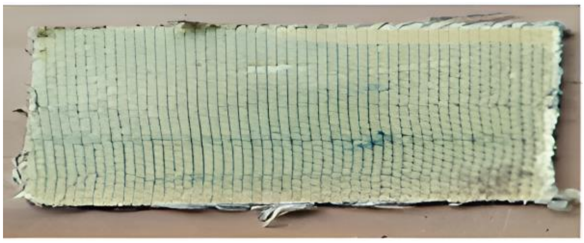

Fig. 9: Impact test specimen of 5 mm thickness

2.3 Specimen Preparation

The specimens used for impact and ILSS testing were prepared based on ASTM standards. Each specimen was prepared with precise dimensions to ensure consistency in testing.

2.3.1 Impact Test Specimens

Specimens used for the impact test were prepared in accordance with ASTM D256 and were 63.5 mm × 12.7 mm × thickness (3 mm or 5 mm) in size. To ensure consistent crack propagation during tests, the specimens mentioned were notched. Specimens prepared for the impact test are shown in Fig. 9 and 10.

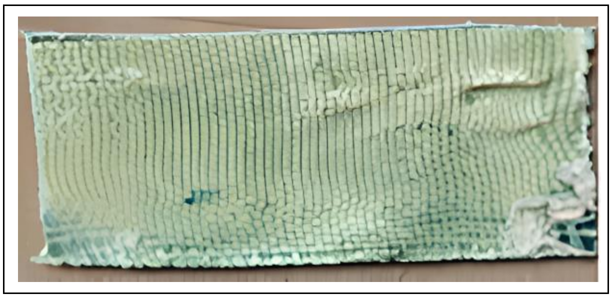

Fig. 10: Impact test specimen of 3 mm thickness

2.3.2 ILSS Test Specimens

Specimens used for the ILSS test were prepared according to ASTM D2344. The dimensions were 25 mm × 6 mm × thickness (3 mm or 5 mm). The prepared specimens for the ILSS test are shown in Fig. 11 and Fig. 12.

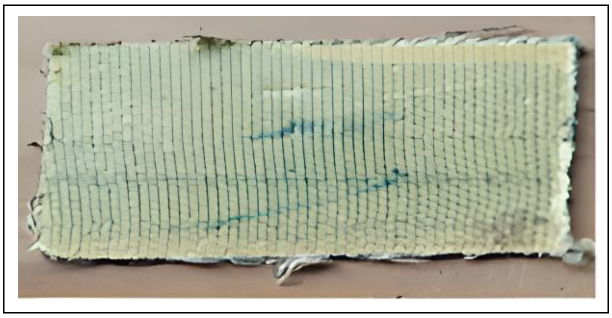

Fig. 11: ILSS test specimen of 5 mm thickness

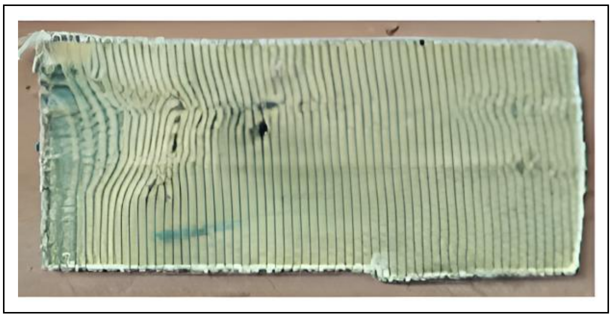

Fig. 12: ILSS test specimen of 3 mm thickness

2.4 Testing Procedures

2.4.1 Impact Testing

The Charpy impact tester was used to evaluate the impact resistance. The specimen was gripped in fixtures and broken by swinging a pendulum and the energy absorbed during the break was recorded. The test provides information regarding the composite's reactivity to sudden forces.

2.4.2 ILSS Testing

Interlaminar shear strength test was performed on a universal testing machine in a three-point bending arrangement. The specimens were subjected to a constant crosshead speed until failure and the maximum load was recorded.

3. RESULTS AND DISCUSSION

3.1 Impact Resistance

Charpy impact test was used to study the impact resistance of the hybrid composites. The absorbed energy recorded for 3 mm-thick specimen was 12.5 J, while for 5 mm-thick specimens, it was 15.8 J. It was noted that with an increase in the thickness of the specimen, there was greater bonding and stronger energy absorption.

The hybrid composite performed much better against impact on 3 mm and 5 mm samples than asbestos or cement. Although asbestos and cement absorb lower amounts (in the range of <6 J and <4 J, respectively), the composite was also competitive with GI (10–20 J). Extra thickness absorbed more energy and, thus, showed better performance. Impact strength comparison is illustrated in table 3 and Fig. 13.

Table 3. Impact strength comparison

S. No.	Materials	Impact strength (J)
1.	Asbestos	3 to 6
2.	GI	10 to 20
3.	Cement	1 to 4
4.	3 mm composite	12.5
5.	5 mm composite	15.8

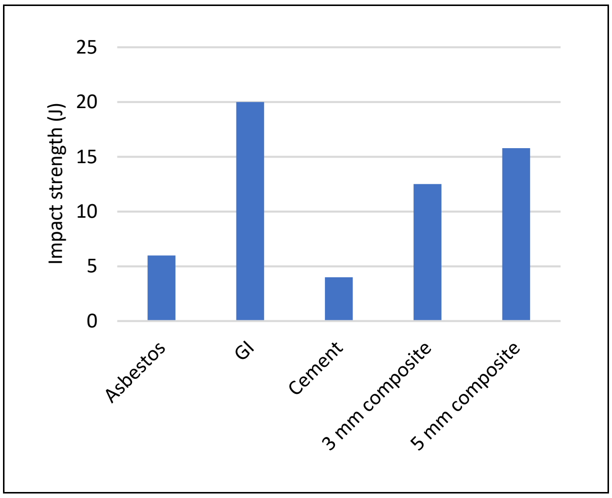

Fig. 13: Impact strength comparison

3.2 Interlaminar Shear Strength

Three-point bending test was used to evaluate ILSS. Table 4 shows the obtained ILSS values upon testing. The ILSS obtained for the 3-mm specimen was 6.8 MPa, whereas it was 8.4 MPa for 5-mm specimen. These values represent strong interfacial bonding and delamination resistance of the composite.

The hybrid composite showed good ILSS compared to regular materials. The ILSS of the 3 mm and 5 mm specimens were 6.8 MPa and 8.4 MPa, respectively, leaving behind cement and asbestos, which exhibit a very low shear strength (2–5 MPa).

The enhanced performance of a composite supports its use in light-weight, high-strength applications despite higher GI values (50–150 MPa). Table 4 and Fig. 14 illustrate the comparison of ILSS for different materials used.

Table 4. Interlaminar shear strength comparison

S. No.	Materials	ILSS (MPa)
1.	Asbestos	2 to 5
2.	GI	50 to 150
3.	Cement	2 to 3
4.	3 mm composite	6.8
5.	5 mm composite	8.4

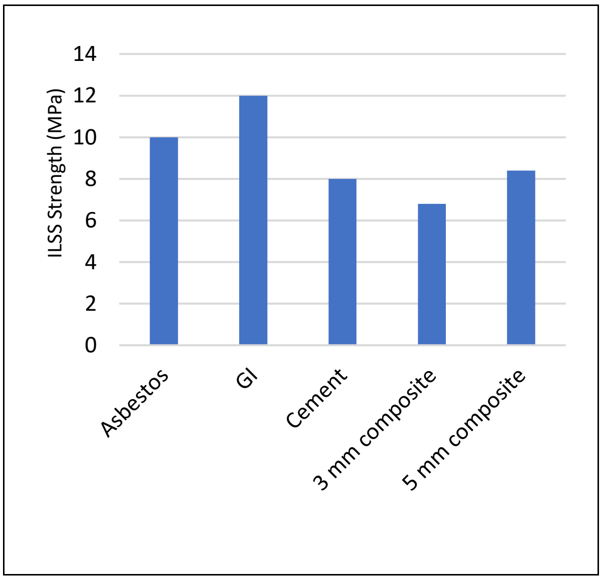

Fig. 14: ILSS comparison

3.3 Thickness Dependence

The results show that increasing composite thickness improves both impact resistance and ILSS. This is due to the increased fiber volume and better matrix-fiber adhesion in the thicker laminates. The drawback is the added material weight, which is a key factor in weight-sensitive applications.

3.4 Failure Modes

The specimens exhibited controlled crack propagation both in matrix material peripheries and efficient dissipation of energy during impact testing. The ILSS tests revealed that the failure was mainly interfacial with negligible fiber pull-out, indicating good bond between the fibers and the matrix.

3.5 Comparison with Conventional Roofing Materials

The mechanical performance of the hybrid composite was found to be much higher than that of the common roofing materials. The ILSS and impact resistance values were much higher than those of cement and asbestos and comparable to GI performance. The lightweight and ecological advantages of the composite make it a promising alternative in modern construction needs.

4. IMPLICATIONS AND POTENTIAL APPLICATIONS

Hybrid composites have the potential to solve significant structural problems, as highlighted by this study. The enhanced impact resistance and ILSS observed in the composite showcase their resilience suited for high-stress scenarios.

4.1 Implications of the Findings

The proposed hybrid composite material can withstand sudden dynamic loads, such as those found in debris impact, making it perfect for roofing and cladding systems in regions impacted by extreme weather. High ILSS values indicate good bonding between the layers, which reduces the chances of delamination at any applied shear stress. All of these properties combined make the composite long-lasting and reliable for structural applications.

4.2 Potential Applications

The hybrid composite possesses unique mechanical properties, making it ideal for various applications, including roofing and cladding. Its high impact resistance and low weight make it particularly well-suited for roofing systems exposed to extreme winds or hail. Additionally, its ILSS values qualify it for load-bearing components, while its exceptional impact resistance enhances its effectiveness in protective structures.

4.3 Sustainability and Environmental Benefits

By incorporating natural fibers, the composite reduces its environmental impact. Its durability reduces the need for frequent replacements, aligning with sustainability goals that promote responsible construction and lower the global carbon footprint.

4.4 Future Research Directions

Future research can further expand the applications of composites by optimizing the fiber-matrix ratio to achieve the ideal balance between weight and performance, exploring additional natural fibers to enhance sustainability, and conducting long-term environmental exposure tests to assess durability.

5. ENVIRONMENTAL IMPACT AND SUSTAINABILITY ANALYSIS

5.1 Environmental Benefits of Hybrid Composites

Use of synthetic material can be reduced by replacing it with this hybrid composite and thereby greatly decreasing the overall carbon footprint of a product. Additionally, using composites (like ones made with hemp) with low requirement of water and chemical pesticides, significantly reduces transportation emissions and energy needed for installation as it is much lighter than conventional materials.

5.2 Comparison with Traditional Materials

Conventional materials like cement, GI are a significant source of CO_2 emissions, asbestos is harmful to health and these are challenging to dispose of. On the other hand, hybrid composites provide a sustainable solution with low energy consumption and less waste generation.

5.3 End-of-Life Considerations

The blend of the natural and synthetic components in hybrid composites makes their recycling difficult. Mechanical recycling and chemical recycling methods like pyrolysis are promising pathways to recover fibers and resin. It also guarantees construction life due to the endurance of the composite that decreases the frequency of replacements.

5.4 Lifecycle Assessment (LCA)

Preliminary LCA studies indicate that the hybrid composite has 30% lower carbon footprint than asbestos and cement. This reduction is consistent with global efforts to pursue sustainable building practices and materials.

6. POTENTIAL FAILURE MODES

6.1 Environmental Factors

Composite materials can degrade even with exposure to moisture, UV radiation, and extreme temperature over time. This involves wear and tear of the matrix-fiber interlocking interface due to moisture absorption and surface damage by UV exposure. These risks can be mitigated with proper protective coatings and regular maintenance.

6.2 Mechanical Stress

Prolonged mechanical loading may lead to fiber fracture, matrix cracking or interface debonding in the composite. Additionally, localized damage and delamination may occur due to shear stress during impact events. Variations in the fiber-matrix ratio and improvements in interfacial bonding can provide resistance to these failure modes.

6.3 Long-term Durability

Long-term use studies are needed to see how a composite works in real-world scenarios. Tests such as accelerated aging can recreate environmental stressors and mechanical fatigue to allow life prediction.

7. CONCLUSION

This work is a novel approach for hybrid composite prepared from Kevlar, hemp, and carbon fibers in epoxy matrix for potential structural applications. Compared to conventional materials, the composite shows better impact resistance and interlaminar shear strength, making it well-suited for extreme conditions. Its lightness and sustainability advantages make it important for contemporary building methods. Future works may be carried out to optimize composite design and durability over time for wide application of the technology.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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