Research Article

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Experimental Investigation on Mechanical and Microstructural Properties of Hybrid Composite Materials for Ballistic Armor Applications

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ABSTRACT

Recently, industries have increasingly required lightweight materials with high strength for specific applications, such as in the manufacturing of ballistic armor. In this work, three synthetic fibers are used: Kevlar, carbon, and glass fiber, and two different sample laminates are fabricated. The fibers are arranged using a hand lay-up process. Out of the two samples, one includes Expanded Polyethylene (EPE) foam—to increase the thickness—while the other does not contain EPE foam. The samples are fabricated in a specific fiber sequence, starting with Kevlar, followed by carbon, and then glass fiber. In the sample with foam, two EPE foam sheets are used and placed between two sequential layers of fibers. Mechanical and microstructural characterization was performed, including tensile testing, flexural testing, DMA testing, and SEM analysis, and the corresponding results were obtained. These fiber laminates are intended for ballistic armor applications, where the three fibers contribute by reducing weight, increasing strength, and enhancing performance, thereby preventing bullet penetration and ultimately saving human life. Advanced materials like Kevlar, ceramic plates, and ultra-high molecular weight polyethylene are used in modern ballistic armour to offer lightweight, yet effective, protection against a range of threat levels, including rifle and handgun ammunition. With continuous research aimed at enhancing protection-to-weight ratios and multi-threat capabilities, these protective systems go beyond personal body armour to include vehicle armouring, aircraft protection, and stationary barriers for critical infrastructure.

Keywords: Hybrid polymer composite materials; Tensile test; Flexural test; DMA test; Microstructure analysis.

1. INTRODUCTION

In recent years, there has been a growing demand for advanced materials that combine the beneficial properties of different constituents to achieve superior performance and versatility. One such class of materials that has gained significant attention is hybrid polymer composites. These innovative materials integrate two or more distinct components, typically polymers and reinforcing fillers, to create a synergistic blend that capitalizes on the strengths of each element (Abtew *et al.* 2019). Different interfaces divide these two phases. High specific strength and stiffness, good corrosion resistance, and good fatigue resistance are the most useful properties of composites. Advanced composite materials, having reinforcing fibers in a resin matrix, are used in transportation and defense industries. Because of their excellent strength-to-weight ratio, laminated composite materials are widely used in mechanical, marine, aeronautical, protective gear, and automotive structures (Benzait and Trabzon, 2018). Engineers and researchers possess the capacity to customize composite materials to fulfill certain performance criteria by meticulously choosing and regulating the characteristics of nanofillers, such as their kind, size, and concentration. These tailored composite materials can exhibit a wide range of desired properties, including but not limited to flexibility, transparency, thermal stability, and flame resistance. In conclusion, nanofillers play a paramount role in enhancing the performance and functionality of composite materials across various industries. Their intrinsic characteristics, such as the ability to improve structural integrity, facilitate thermal and electrical conduction, and customize material properties, make them indispensable in advancing sophisticated materials for fields like aerospace, automotive, electronics, and related domains. Nonetheless, the successful integration of nanofillers requires meticulous engineering and a thorough evaluation of safety factors, making this a captivating yet demanding domain in the field of materials science (Braga *et al.* 2017; Luz *et al.* 2015).

1.1 Multi-layered Armor System (MAS)

Hybrid polymer composites offer a wide range of remarkable characteristics, making them highly desirable in various industries, including aerospace, automotive, construction, and electronics. By combining different types of polymers, such as thermosetting and

thermoplastic resins, along with diverse fillers like carbon fibers, glass fibers, nanoparticles, or natural reinforcements, manufacturers can tailor the composites to meet specific engineering requirements. The key advantage of hybrid polymer composites lies in their ability to overcome the limitations of individual materials. For instance, by blending a tough and flexible polymer with a stiff and strong reinforcing material, the resulting composite can exhibit enhanced mechanical properties, such as high tensile strength, improved impact resistance, and better fatigue performance. Moreover, hybrid composites can offer unique combinations of electrical, thermal, and chemical properties, enabling them to excel in multifunctional applications (Grujicic *et al.* 2006; Jambari *et al.* 2017; Luz *et al.* 2017).

The front ceramic tile of a conventional multilayer armor system absorbs the vast majority of the impact energy, allowing it to stop the 7.62 mm fast bullet's perforating force. Not only does bullet spalling contribute to energy dissipation, but the breakage of brittle ceramics does as well. Both the bullet and the ceramic can shatter with enough force to cause fatal injuries if they collide at high speed. Therefore, an additional layer is added behind the primary ceramic to dampen the shock wave generated by the collision and the resulting fragment explosion. The second layer of a Multi-layered Armor System (MAS) configuration is often Kevlar, followed by a ductile material to stop projectiles from entering the body. The amount of energy absorbed by an MAS is dependent on the shock impedance at the layer contact. After a projectile impact in the front layer, a compressive transverse wave travels through the ceramic, encountering several reflections on its way. The kind of waves reflected depends on the impedance of the interface. When the compressive component of a shock wave encounters a second layer with a lower density, like Kevlar™, the wave is reflected as a tensile wave, which helps efficiently break the ceramics. More effective energy absorption allows for a thinner second layer (Mawkhlieng *et al.* 2020; Medvedovski, 2006; Morye *et al.* 2000).

1.2 Ballistic Armor

The concept of ballistic armor, which consists of steel plates and serves as a protective barrier against sharp objects or projectiles, emerged in 1538. Bullet impact trauma has been mitigated by advancements in body armor design and material selection, which have also increased energy absorption while decreasing weight. Two common types of body armor are hard body armor and soft body armor. Cetal, ceramic, or composite fibers are used to reinforce hard body armor. Military troops use them to defend themselves from high-speed projectiles during high-risk missions. On the other hand, multiple layers of high-performance fabrics are used for soft body armor, which is used to protect the torso and extremity regions. Absorption of the bullet or fragment's energy is the process through which ballistic protection is obtained. Due to their mass and projected velocity, these projectiles or fragments contain a significant amount of kinetic energy. In this paper, we will delve into the fascinating world of hybrid polymer composites, exploring their composition, manufacturing techniques, properties, and diverse applications. Additionally, we will discuss the latest advancements and ongoing research efforts in this field, highlighting the potential implications and future prospects of these innovative materials (Naik *et al.* 2020). The novelty of this research is to develop hybrid polymer-reinforced composite materials and analyze the mechanical properties of the hybrid composite. The integration of nanofillers into composite materials serves to enhance their mechanical properties. These materials frequently demonstrate improved stiffness, strength, and toughness. The incorporation of carbon nanotubes into a polymer matrix has been observed to yield a substantial enhancement in both the tensile strength and modulus of the resulting composite material. Several types of nanofillers, including carbon nanotubes and graphene, possess exceptional conductivity properties for both heat and electricity. When included in composite materials, they have the potential to significantly augment thermal and electrical conductivity, rendering these materials highly advantageous in various applications such as electronic devices and aeronautical components (Karthik *et al.* 2022; Bucura *et al.* 2023; Lin *et al.* 2023).

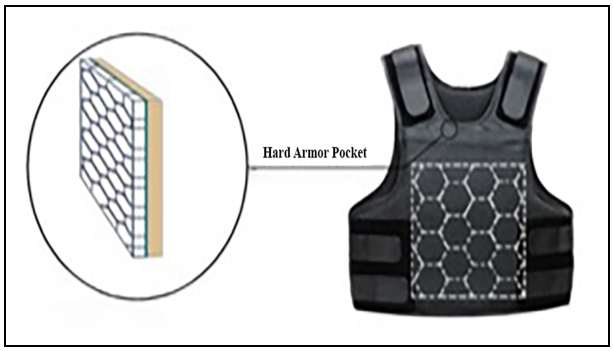


Fig. 1: Multi-layered Armor

2. MATERIALS AND METHODS

Kevlar (para-aramid), a strong and heat-resistant synthetic fiber, is created by initiating a chemical reaction between an acid and a nitrogen and hydrogen-containing chemical solution. The molecules of Kevlar have a strong, ring-like structure, similar to that of benzene. Due to its chemical nature, it spontaneously forms microscopic straight rods that pack tightly together. Long chains are formed when the ring-like aromatic molecules join. Due to its impact resistance, high strength, and low weight, Kevlar is the most commonly used fabric for making armor against bullets from handheld weapons. The wide range of applications include aerospace, road and marine transport, sports

equipment, prostheses, surgery, X-ray equipment, implants, and tendon/ligament repair. Glass fiber is a special synthetic fiber consisting of numerous fine fibers of glass. Glass fiber has a lesser stiffness than other reinforcing fibers, but it has the particular benefit of combining high strength with low density and, most importantly, at low cost; it is used in the food processing sector, chemical industries, sectors related to metals and mining, aerospace, and defense. Another name for epoxy resins is polyepoxides, which are reactive prepolymers and contain an epoxide group. EPE foam, made from expanded pellets (EPE beads) using blowing agents, is formed by expanding the material into a mold in a steam chest. The method is similar to the one used in the production of expanded polystyrene foam (Regassa *et al.* 2014; Sikarwar *et al.* 2012; Krishnasamy *et al.* 2022). Figures 1 and 2 show the reinforcement materials.

Table 1: Mechanical properties of the fabricated Hybrid composites

S. No.	Width (mm)	Thickness (mm)	Breaking Load (kN)	Tensile Strength (MPa)	Flexural Strength (N/mm^2)	Impact Strength (J)	Hardness in Shore 'D'
1	14.9	9	6.1	135	26.144	2	55
2	14.6	7	6.1	180	13.768	4	60

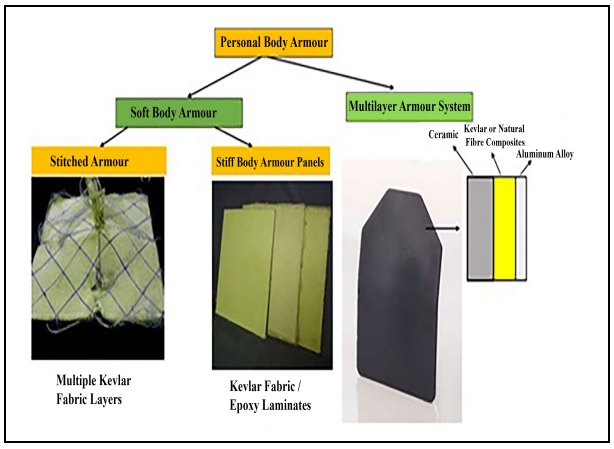


Fig. 2: Types of Armor



Fig. 3: Carbon, glass, Kevlar fibers, and EPE foam materials

One of the earliest and most frequently used methods for making composites is the hand lay-up process. Impregnating layers make fiber-reinforced plastic (FRP) of reinforcing fibers (often fiberglass, carbon fiber, or aramid) with a liquid resin matrix (typically epoxy, polyester, or vinyl ester) laid down by hand on a mold. Although time-consuming, this method is widely used because of its low cost, ease of implementation, and potential for creating elaborate composite structures. The first step is to make a mould, which is a negative reproduction of the final design. To prevent the composite from adhering to the mould, it is often constructed of fiberglass or metal and treated with a releasing agent. Reinforcing fibers, often called "prepregs" or "fabric," are placed by hand in successive layers on the mould. The mechanical characteristics and strength of the finished composite can be tailored by adjusting the orientation and quantity of fiber layers. After the fibers have been laid down, the liquid resin is applied with brushes, rollers, or sprayers so that it covers the whole surface of the fiber stack. The resin permeates the fiber layers, creating a matrix that bonds and supports the composite (Fayaz *et al.* 2022; Karthik *et al.* 2023; Ramesh *et al.* 2023; Jebarose *et al.* 2023). Figures 3 and 4 show the hand lay-up process.

A consolidating tool, like a roller or squeegee, is used to press the layers together to ensure adequate compaction and to eliminate any trapped air or voids. This method aids in producing a composite with minimal flaws and consistent resin distribution. After the composite has been laid down, it must cure. Curing is the chemical reaction that causes the resin to crosslink and harden into a solid. The resin system and the desired qualities determine the curing time and temperature. Demolding and finishing occur once the curing is complete, and extreme care is used to remove the composite part from the mould. It is possible that further finishing, like reducing the surplus and polishing the surface, will be needed to get the appropriate proportions and quality. Applications where low to medium production numbers, customization, and cost efficiency are paramount often employ the hand lay-up technique. It is important to note, however, that manual handling can cause discrepancies in the mechanical properties of the finished composite by introducing differences in fiber alignment and resin distribution. Since automated techniques like filament winding and automated tape laying allow for greater efficiency and accuracy in mass production, they are frequently favoured. The manual lay-up process is still widely used in the composite manufacturing industry, particularly for prototypes, short-run productions, and specialized applications.

2.1 Hand Lay-up Process

The hand lay-up process, shown in Fig. 4, is the most popular and least expensive open-molding method. In this process, fiber reinforcements are placed by hand into a mold, and resin is then applied using a brush or roller. This method is used to produce both large and small products. It is a straightforward approach for

manufacturing composite materials and is particularly suitable for fiber-reinforced components.

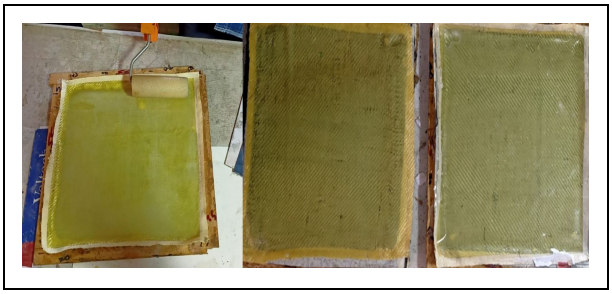


Fig. 4: Hybrid composite laminates

2.2 Fabrication Process

The process began by cutting Kevlar, carbon, and glass fiber sheets into 18 pieces, each measuring 30 cm × 30 cm. A 35 cm × 35 cm wooden platform was then prepared, and a polymer sheet was placed on top. Polyvinyl alcohol was subsequently used to clean the bedding surface. A resin mixture with a total weight of 225 g was prepared, consisting of 200 g of epoxy and 25 g of hardener. This resin was used to bond the composite laminate layers. The Kevlar fiber laminate sheet was laid on the base, and resin was carefully applied over the entire surface using a brush. After resin application, a roller was used to evenly distribute the resin across the fiber sheet. The carbon fiber sheet was subsequently placed on top of the Kevlar layer, and the resin was reapplied and uniformly distributed using a roller. A third layer of glass fiber was applied over the carbon laminate sheet using the same procedure. Finally, another composite layer was placed on top to complete the stack. Bricks were placed over the laminate to aid the curing process. The assembled samples were then air-dried for three days to ensure proper curing. Three distinct lamina samples were fabricated: one incorporating all three fiber types and EPE foam, another comprising the fibers without foam, and a third containing the fibers with a steel plate. All samples were manufactured using the hand lay-up technique. Following the curing process, the laminates were removed from the wooden base, and the excess material was trimmed to the required dimensions using a power saw. The trimmed laminates were then polished to achieve a superior finish. The final laminates measured 30 cm × 30 cm and comprised two types of samples. The laminate containing all three fibers and EPE foam exhibited the greatest thickness, measuring 9 mm. The laminate without EPE foam measured 7 mm in thickness, whereas the one incorporating the steel plate had a thickness of 8 mm.

3. RESULTS AND DISCUSSION

As a part of mechanical characterization, tensile, flexural, and DMA tests were carried out. The test specimens were designed based on ASTM; one sample consisted of all three fibers with EPE foam included in it, and the other sample consisted of only all three fibers without the foam. Table 1 shows the mechanical properties of the developed composites. The mechanical test values for the two samples were taken separately.

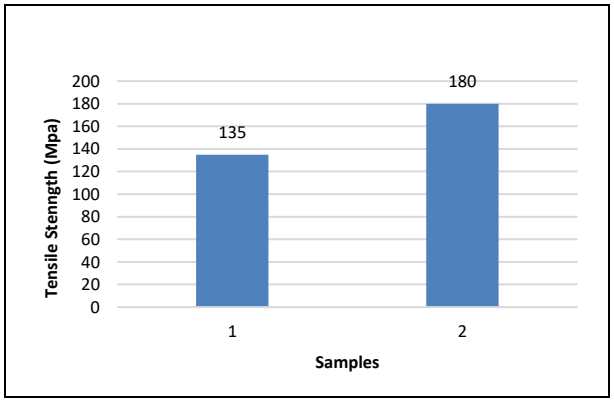


Fig. 5: Tensile strength Analysis of the Hybrid composite

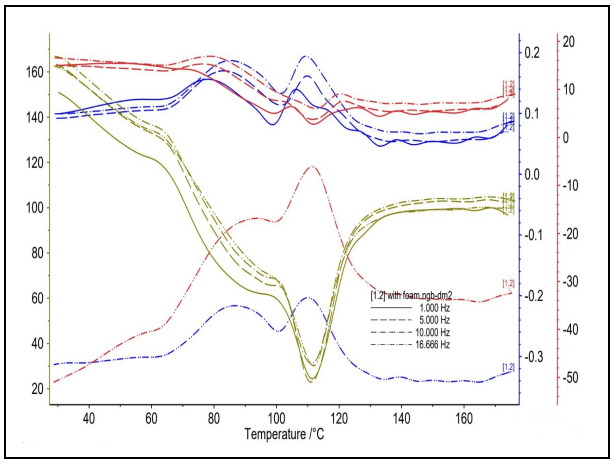


Fig. 6: Dynamic Mechanical Analysis of the Hybrid composite

The tensile strength is important for a material as it has to have the ability to withstand elongation and resist the load applied to it during the process. Naturally, Kevlar fiber is a high-tensile material and is used in various applications across many industries. depicts a bar graph using the data of tensile strength for the two samples. The above Fig. 5 shows that the tensile strength for the sample with foam was 135 MPa, and that without foam was 180 MPa. Thus, the tensile strength is higher in the sample without foam.

Based on the Dynamic Mechanical Analysis (DMA) shown in Fig. 6, the hybrid composite demonstrates distinct viscoelastic behavior across the temperature range from 30 °C to 180 °C. The storage modulus (E') shows the typical thermoplastic behavior, maintaining relatively stable values around 160 MPa at lower temperatures before experiencing a gradual decline as temperature increases, with a more pronounced drop

occurring around 80-100 °C, likely corresponding to the glass transition region of the matrix material.

The DMA results reveal that this hybrid composite possesses good thermal stability and damping characteristics, making it suitable for applications requiring consistent mechanical performance across varying temperature conditions, with the glass transition temperature appearing to be in the range of 90-100 °C based on the peak positions in both loss modulus and tan δ curves.

Microstructure analysis of hybrid composite plates is shown in Figures 7 and 8.

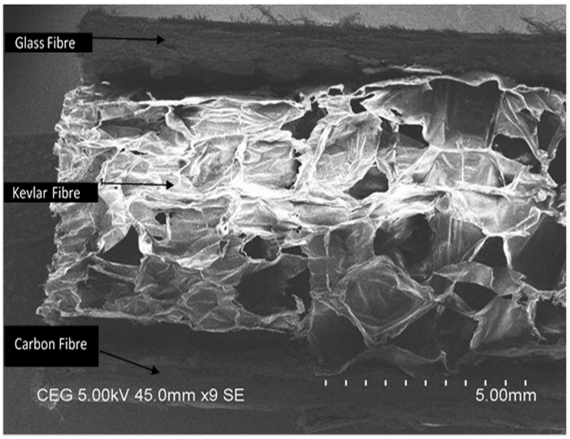


Fig. 7: Microstructure of the fabricated Hybrid composite



Fig. 8: Microstructure of fractured hybrid composites

Based on the SEM images of the two different samples, one with foam and the other without foam, the microstructural analysis reveals the complex fiber architecture and interfacial characteristics of this hybrid composite system. Fig. 7 SEM micrograph (6.00 kV, 45.0 mm, x9 SE, 5.00 mm scale) shows the cross-sectional view of the hybrid composite, clearly identifying three distinct components: glass fiber, Kevlar fiber, and carbon fiber. The image demonstrates the heterogeneous nature of the composite with different fiber types embedded within the polymer matrix. The glass fibers appear as circular cross-sections with relatively smooth surfaces, while the Kevlar fibers show their characteristic fibrillar structure. The carbon fibers are distinguishable by their smaller diameter and darker appearance. The fiber distribution appears relatively uniform, though some clustering of similar fiber types is evident. Fig. 8 micrograph (6.00 kV, 10.3 mm, x1.04k SE, 50.0 µm scale) provides a higher magnification view focusing on individual fiber bundles, particularly showing the longitudinal orientation of the reinforcing fibers. This image reveals the surface morphology and interfacial bonding between the fibers and matrix material. The fibers display good wetting by the polymer matrix, indicating adequate interfacial adhesion, though some minor gaps and voids are visible at the fiber-matrix interface, which could potentially affect the mechanical properties.

The microstructural analysis confirms the successful integration of multiple fiber types within the composite system, with the hybrid architecture potentially providing synergistic effects by combining the individual advantages of each fiber type - the high strength of carbon fibers, the impact resistance of Kevlar, and the cost-effectiveness of glass fibers.

4. CONCLUSION

The composite materials employed in this work, Kevlar, carbon, and glass fiber, are good ballistic materials. Three samples were fabricated using the hand lay-up method. Each sample has Kevlar, carbon, and glass fiber in common, with and without EPE foam inclusion. The purpose of adding EPE foam was to increase the thickness as well as the stiffness of the laminate. The two samples were cut into test specimens as per ASTM standards and were tested for mechanical and microstructural characterization. The mechanical tests carried out were a tensile test, DMA, and SEM analysis. The tensile strength for the foam sample was 180 MPa, without foam was 135MPa. The flexural strength was 19.95 MPa for the foam sample and 32.32 MPa for the sample without foam. The samples were also tested for their viscous and elastic behavior against different temperatures and times. The measurements for physical properties were made on the samples against the temperature, and the microstructural properties were observed with the help of SEM images. The hybrid polymer matrix composite is useful for many applications across various industries. One such application where the usage of such polymers is made is the ballistic armor, where these polymers are replaced with conventional metals due to their improved properties and performance. A bullet has its energy reduced as it tries to fight its way through.

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CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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