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Kevlar-based Composite Material and its Applications in Body Armour: A Short Literature Review

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Abstract. Kevlar is a synthetic fibre which has gained worldwide attention due to its numerous industrial applications. It is mostly used in combination with other materials and acts as an effective composite material. Scientifically known as poly(p-phenylene terephthalamide), the Kevlar monomer has 14 carbon atoms, ten hydrogen atoms, two nitrogen atoms and two oxygen atoms. A Kevlar polymer chain can have monomers ranging from five to one million bonded to each other with a molecular formula of $[-CO-C6H4-CO-NH-C6H4-NH-]_n$, where *n* represents the number of monomers. Kevlar has a wide variety of applications ranging from bicycle tyres to aerospace applications. Based on the applications, Kevlar fibres are graded in various ranges. This paper provides insight into major research on Kevlar, especially in defence applications.

Keywords: Kevlar, fibres, armour, composites, polymer-matrix, laminates, bullets, impact tests

1. Introduction

Kevlar has many desirable properties when compared to other synthetic and natural fibres, which gives it a primary position in various load-bearing applications. Its most important property is its high tensile strength to weight ratio, which means that, when compared to a normal material, it has higher tensile strength at a lower weight. Kevlar is stable in most chemical environments, yet it can undergo degradation when exposed to some aqueous acids, bases or sodium hypochlorite. Researchers have proved that it can be used as a substitute for steel, since it is almost five times stronger than steel. Kevlar and polyethylene fibres, when knitted and woven with a composition of 50% each, has shown a higher cut resistance index in composite samples, making it suitable for use in sportswear and domestic applications [1].

Kevlar fabric shows a tensile strength of 3620 MPa and a very low relative density of 1.44, which is ideal for helmet, body armour and ballistic applications, where strength-to-weight ratio is especially important. Armour materials are meant to protect human beings in the defence field from high impact bullets. Currently, several research initiatives are being carried out to reduce the weight of armour using Kevlar-based composite material without compromising the strength of the armour. Synthetic fibres produced through polymerisation are the major constituents of woven Kevlar fabric, which can be used in bulletproof vests [2,3].

Recently, many studies have been done on the development of Kevlar in body armour applications and on optimising the required mechanical properties. Some researchers have focused on optimising the constituent materials in the composites so that the desired properties can be achieved without compromising on weight reduction. As a highly promising area of research, there is still a lot of work to be done related to manufacturing, testing and the environment in which the product is applied. In light of this, this paper provides an overview of some important studies on Kevlar-based composite materials.

2. Types of Kevlar

This section discusses the different varieties of Kevlar materials that are normally available and their usage in various applications.

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2.1. Kevlar 29

This grade of Kevlar is normally used in brake linings, armour for vehicles, cables and other industrial applications. It is an ideal candidate in these applications due to its light weight, non-flammability and ability to withstand high temperatures. The breaking strength of this material is 338 N, and it has a tensile modulus of 70.5 GPa. The percentage elongation at breaking point for this Kevlar type is almost in the range of 3–4% [4]. It has also been observed that woven fibre of Kevlar 29, along with Al_2O_3 powder/epoxy acting as a hybrid composite, has a high energy level when impacted with different types of projectiles [5].

2.2 Kevlar 49

This type of fibre is mainly used in aircrafts as reinforcement due to its improved properties of low weight and high tensile strength. The percentage elongation at breaking point for Kevlar 49 has been observed to be in the range of 2–2.5% with a tensile modulus of 112 GPa. This estimate shows that the percentage elongation is 30–40% less and tensile modulus is 30–50% more than Kevlar 29 fibre. The breaking strength of Kevlar 49 is in the range of 264 N. The improved properties are attributed to the perfect orientation of polymer chains in the Kevlar 49 type when compared to the Kevlar 29 type aramids. This is because Kevlar 29 is heat treated at a high temperature under tension to obtain Kevlar 49, which causes less water molecules to pass through [4,6]. The specific heat of both Kevlar 29 and 49 grades is approximately 2010 J/kg K at 100 °C, and the shrinkage of both these fibres was found to be less than 0.1% at 1000 °C [4].

2.3 Kevlar 149

Kevlar 149 has high impact strength when compared to Kevlar 29 and 49, enabling it to be used in applications such as bulletproof vests, tankers and ballistic resistive missiles. However, Kevlar 149 has higher density and toughness when compared to the other types of Kevlar fibres discussed above. The tensile modulus and tensile strength of the Kevlar 149 type was found to be in the range 186 GPa and 3.4 GPa, respectively. The percentage elongation at breaking point was found to be 2% [7]. The comparison of tensile modulus and breaking strength of different grades of Kevlar is shown in Table 1, and a bar chart representing the percentage elongation at breaking point is shown in the Figure 1.

Table 1. Comparison of tensile modulus and breaking strength of Kevlar 29, 49 and 149.

Kevlar grades	Tensile modulus (GPa)	Breaking strength (N)
Kevlar 29	70.5	338
Kevlar 49	112	264
Kevlar 149	186	-

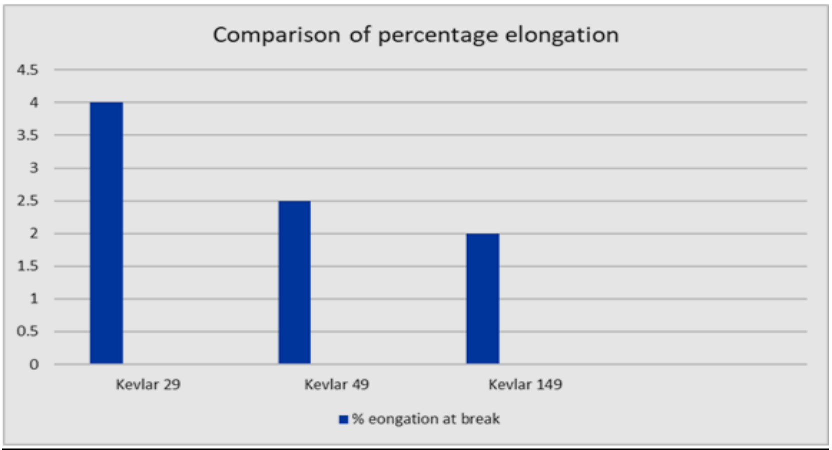

Figure 1. Comparison of percentage elongation of different grades of Kevlar.

3. Kevlar in body armour applications

The use of Kevlar material in body armour has been widely researched since 1970, and some studies have demonstrated excellent results in this area. Previously, steel-based body armour was widely used, but its major drawback was increased weight. In contrast, Kevlar as woven fabric in this application has showcased its capacity to address this concern by minimising the steel material, since it has a high strength-to-weight ratio.

It has been found that there is no direct linear relationship between the type and thickness of Kevlar measured in grams per square metre (GSM), if the combination arranged in layers has the same weight. The capability of different layers of Kevlar material with 160 GSM, 200 GSM and 400 GSM along with ballistic gel was studied, and it was observed that 200 GSM Kevlar is the most effective in stopping a 9 mm projectile [2]. From the modelling and simulation of a 20-layer Kevlar 29 fabric with polyester, it was reported that the composite withstood the energy of a bullet impact with a muzzle velocity of 720 m/s fired from a distance of 10 m [8]. Three combinations of composite plates embedded with Kevlar 29 were fire tested with bullets of 5 mm and 9 mm from a handgun and also from a 7.62 mm bullet from a Kalashnikov gun with bullet speeds of 200 m/s, 360 m/s and 760 m/s, respectively. In this study, the target plate was placed at 5 m from the handguns and 25 m from the Kalashnikov gun, and the kinetic energy absorbed before and after the impact was noted. The tests were also done with an air gap between the plates. The air gap was reported to impose a positive effect on the absorbed energy with the presence of Kevlar, providing high stiffness to the composite plate [9]. Upon being subjected to the strain test, the intra-ply and inter-ply Kevlar/basalt fibres in polypropylene matrix demonstrated that the former failed due to matrix cracks, whereas the latter failed due to delamination and multiple shear. Firing tests were also carried out in this study, and it was observed that the presence of Kevlar alone could not provide resistance to bullet firings. Firing resistance depended on many other factors, such as the grade and thickness of Kevlar fibres and the presence of other backup reinforcement like ceramics. Apart from these, a hybridisation scheme along with firing parameters like the type and speed of the bullet and the angle of firing determined the strength of the composite material [10].

Composite laminates were prepared with epoxy resin and Kevlar 29 woven fabrics with plies ranging from 8, 12, 15 and 19 with different thickness values. With these laminates having different orientations of fibres, the material properties were identified. These laminates were placed at 10 m from the gun point, and the impact of parabellum 9*19 mm bullet was done by firing it at a velocity of 390±10 m/s. The impact and residual velocities were noted for each firing, and five sets of readings with each thickness value of laminates were taken. It was found that the average energy absorption by the laminates increased when the thickness was increased. The energy absorbed by the laminate was equal to the reduction in kinetic energy of the bullet. A very interesting point from the experiment was that the damage on the front side of the plate was less when compared to the back side for all the thickness values of laminates. It was enumerated that, owing to the tensile failure of fibres at the back side, the crack propagation was perpendicular to its orientation. In addition, it was found that the layup of laminates had a significant effect on the energy absorption capacity of plate, with 0/90 layup having maximum value with all wall thicknesses. If the laminate was thin, the front part of the plate mostly failed in compression–shear mode and the back part in tension–shear mode [11].

In a related study, three prototypes were manufactured, and firing tests were done with different types of bullets and guns. The prototypes had a dimension of 100*100 mm, in which prototypes 1 and 2 had eight layers of Kevlar sheets impregnated in epoxy resin and aluminium oxide ceramic materials, respectively. Prototype 3 was manufactured with eight layers of Kevlar sheets stacked with epoxy resin and had no backing material. It was observed that prototype 1 successfully defended the 9 mm bullet fired from a handgun in a range of 4–5 m and also from an MP-5 rifle in a range of 10–11 m. It was also noted that prototype 2 successfully defended the handgun and MP-5 rifle with the same parameters in previous tests. For prototype 3, the material safeguarded the penetration of the bullet through the Kevlar layers. However, it was noted that, when the Kevlar layers were removed, the composite material failed to arrest the movement of the bullet [12]. A higher damping ratio was observed on the Kevlar/epoxy composite when compared to carbon and glass fibre composites due to the fact that Kevlar has higher flexibility in comparison to the other two [13]. Ballistic tests were conducted on Kevlar/fabric and Kevlar/epoxy composites with projectiles launched at different speeds. Kevlar/fabric samples were tested with velocities ranging from 140–260 m/s, and Kevlar/epoxy samples were tested at 60–178 m/s. It was observed that Kevlar fabric can absorb 100% of the projectile's energy when launched at 140 m/s velocity, since the residual velocity was nearly zero, which implies there were no perforations on the material. However, the Kevlar/epoxy composite was able to absorb only 50% of the energy at the same launching speed of the projectile [14].

In a previous study, it was found that Kevlar fabrics treated with 100 nm spherical silica nanoparticles as shear thickening fluids (STF) in different weight percentages contributed to higher energy absorption, which highlights the fact that it can be used in soft body armour applications. The energy absorption for untreated samples at failure was observed at 40% and doubled to 80% when treated with STF [15].

Another piece of research focused on the low velocity impact response of Kevlar and basalt 3D laminates separately and on a hybrid composite laminate that consisted of both Kevlar and basalt, which were manufactured by impregnating polypropylene fibre in between the laminates by using the compression moulding technique. It was shown experimentally that the energy absorption by the hybrid laminate is higher in the range of 180 J when compared to the other two. In this study, the presence of Kevlar fibre in the thickness orientation and its ability to deform in tension was attributed to higher damage extension for hybrid laminates [16].

In a similar study, shear thickening gel (c-STG) combined with Kevlar fabrics offered excellent anti-impact resistance when used in body armour. The low velocity impact test results showed that the maximum centre force of c-STG-Kevlar fabric was in the range of 5700 N, which was only half that of pure Kevlar fabric, and, in the high velocity ballistic test, it significantly absorbed the energy of monolayer c-STG/Kevlar fabric, which amounted to 21% of the impact energy [17].

The ballistic test results of composites made by incorporating basalt and Kevlar fibres with polypropylene arranged symmetrically and non-symmetrically have been compared, and it was proved that symmetric arrangement can withstand the impact of a 9 mm bullet in the range of 365–425 m/s, while non-symmetric arrangement cannot [18].

Short fibres of Kevlar have been used to toughen carbon fibre reinforced polymer laminates, which significantly improved impact strength and failure strain values when tested under low velocity impact. In low velocity impact tests, an indenter having a certain amount of mass is dropped from a height, and the respective velocities are noted with the help of laser attachments, and the impact loads are measured by using piezoelectric load cells [19]. The addition of nano clay and graphene inclusions at 10% weight of the Kevlar/epoxy composite was subjected to a low velocity impact test with a hemispherical drop weight of 15.875 mm diameter and 6.27 kg weight. The results of this study proved that, with an increase in the weight of nano clay, the impact resistance also increases, without any effect on the volume fraction of graphene. The presence of graphene can reduce the damage area of the specimen, UV degradation and water absorption [20]. The characterisation of damaged composite plates has shown that failure occurs by delamination, fibre pull-out and breakage, which depend directly on parameters such as fabric structure, velocity of impact, ply interaction and plate thickness [21]. Hence, in the development of body armour using Kevlar fibres, some important Kevlar composite parameters, test methods and material characterisations are to be considered, as shown in Figure 2.

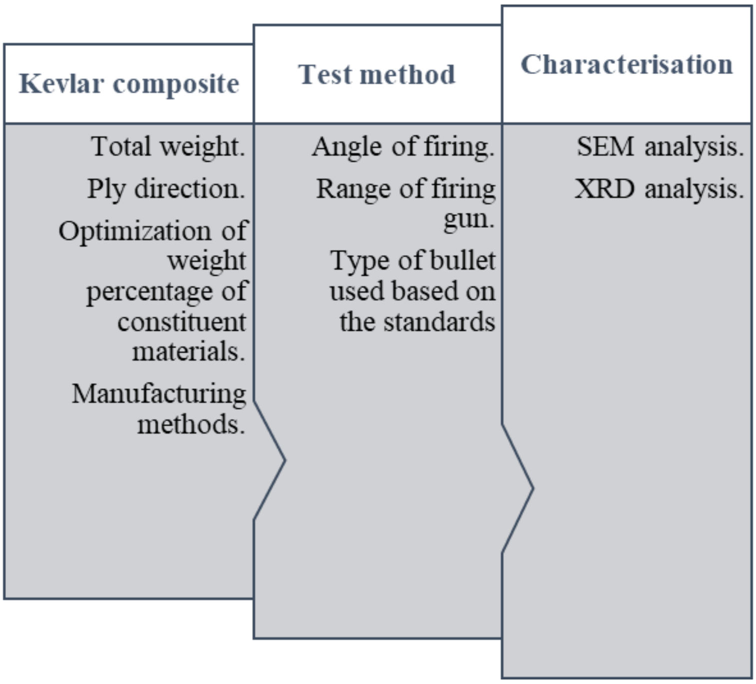

Figure 2. Areas of focus in the development of Kevlar-based body armour.

3.1 Flexibility test

These types of tests are conducted on materials that are supposed to have flexibility properties. In the case of Kevlar body armour, flexibility plays a vital role in absorbing the energy of the bullet after it hits the body. The impact response of Kevlar and rubber composites has been studied, in which a test for flexibility and high velocity impact was performed and compared with finite element simulation methods by using CATIA. Kevlar fabric, having 0.23 mm thickness and 180 GSM, was impregnated with high hardness (HH) rubber and low hardness (LH) rubber as separate specimens by using a hydraulic press. These specimens were made in two sets: one with two layers of Kevlar and the other with four layers, with final thickness of 1 and 2 mm, respectively. The drake tests were conducted by using a weight of 20 g, and the corresponding angle of bend was noted. It was found that, when compared to pure Kevlar fabric, the composite with HH rubber plummeted slightly, which means that neat Kevlar is more flexible. A schematic diagram of the drake flexibility experimental setup is shown in Figure 3.
The deformed shape of the specimen after the application of weight is shown with dotted lines, and the angle of deformation is represented as ϴ, where the higher the value of ϴ, the higher the flexibility of the specimen is [22].

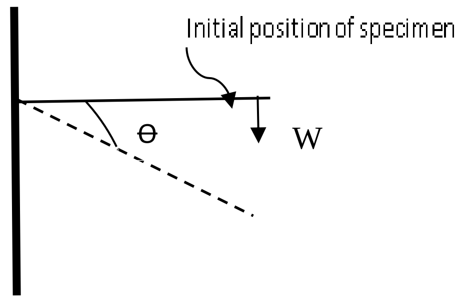

Figure 3. Schematic diagram of the drake test (flexibility test) [22].

3.2 High velocity impact test

The basic theory behind the velocity impact test is finding out the energy absorbed by the target body, which can be found by using the simple kinetic energy equation. Firing tests on the Kevlar/HH rubber composite was conducted with hemispherical bullets fired at a velocity of 150 m/s from a gas gun having a pressurised barrel at 120 bar. The initial velocity is represented by V_i and residual velocity as V_r in m/s. The energy absorbed (ΔE) is calculated by using the following equation (1), where 'm' is the mass of the bullet in kg.

$$\Delta E = 0.5*m*(V_i^2 - V_r^2) \quad (1)$$

The results of this study prove that the Kevlar/HH rubber composite has better impact performance when compared to the other two specimens in section 3.1. The absorbed energy of the two-layer and four-layer Kevlar/HH rubber composites increased by 53% and 73%, respectively, when compared to neat Kevlar fabric owing to the fact that velocity reduction is directly proportional to the hardness of the rubber [22]. In an experimental study, a hybrid composite was prepared by incorporating epoxy polymer, conch shells and banana fibres in between aluminium plates for effective absorption of impact energy during firing tests. It was observed that the resulting composite material improved tensile and flexural strength, probably due to the presence of banana fibres and conch shells. However, to reveal the effect of each constituent on the bulletproof vest, the scanning electron microscope (SEM) image of bullet marks shows that the presence of banana fibres can cause fire and create a hole in the vest material [23]. A study concentrated on the effect of the stacked basalt and Kevlar hybrid composite in which the high velocity impact test was conducted with the speeds of the projectile at 40, 50 and 60 m/s, where the bullet had a 21.5 mm diameter and 27 g weight. The test plate had four, five and six layers of basalt and Kevlar (both considered), and the plate had a dimension of 13*13 cm. In this study, the number of impacts for failure were noted, and it was found that thickness is directly dependent on the tolerance for impact, i.e. when the thickness increases, the number of impacts required for failure also increases [24]. A multi-layered armour system (MAS) with an epoxy plate and jute fabric at a 30% volume fraction as the intermediate layer was utilised to compare the bullet defence of the armour material with that of Kevlar. The results show that the jute fibre composites are more efficient in absorbing impact energy [25]. In a similar study, improved tensile and flexural strength were observed for a Kevlar/graphene composite under different concentrations of graphene material and different directional orientation of the composites [26].

4. ASTM testing standards used in Kevlar research

The American Society for Testing and Materials (ASTM) provides a streamline for all technical standards that should be followed for testing and developing materials. It is accepted globally by all manufacturers and researchers for ensuring uniformity in standards.

4.1 ASTM D7136/D7136M

This standard specifies the test methods that should be followed in finding the damage resistance of polymer matrix laminates subject to low velocity impacts. The impact tests can be done by dropping a

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mass with a hemispherical indenter, and the height of drop determines the energy of impact. The test specimen, which is normally made in a rectangular shape, will be held in a fixture underneath the weight, and the respective damage resistance properties can be studied. This standard was used in a test where a specimen with a 152.4*101.6 mm cross section was impacted with a 6.27 kg drop weight, the details of which were discussed in section 3 [20].

4.2 ASTM D3039/D3039M-95a
This is the tensile testing standard used for polymer composites in which the force required to break the polymer under the action of tensile load applied by UTM is evaluated. A strain gauge can be used to measure the elongation, and this will assist in plotting the stress–strain diagram to find the tensile modulus. The normal test specimen should have a cross section of 25 mm width and 250 mm length. A test specimen with 10*100 mm dimensions was prepared, and a quarter bridge strain gauge was utilised to measure the strain to figure out the high velocity impact response of Kevlar 29 and Al_2O_3 powder/epoxy composites [5].

4.3 ASTM D7264
The ASTM D7264 standard features a bending test to determine the flexural properties of polymer matrix composites with a rectangular cross section. Under this standard, the test can be conducted on a three-point or four-point loading system. A three-point loading system is simply a supported beam acted upon by a central load. This test can provide data such as maximum flexural stress, flexural strength and maximum strain. The maximum span-to-thickness ratio is specified for this test as 32:1. A specimen with a 100*4.8 mm cross section was tested on a three-point system to identify the damage propagation of a TiNi-Kevlar stitched carbon/epoxy specimen. The displacement rate was given as 1 mm/min, and it was proved that a Kevlar-stitched element requires 20% more energy to deform in comparison to a non-stitched one [27].

5. Conclusion
The use of Kevlar in polymer matrix has a wide scope to open research extremities. The most attractive feature of Kevlar for defence and ballistic applications is its considerable strength at lower weights. It must be noted that only limited research is available utilising Kevlar in ballistic applications, and this paper has covered only the most significant work. The process of hybridisation is mainly utilised by researchers, in which one or more materials in polymer matrix have been developed to understand their behaviour in various applications. The various aspects in the development of Kevlar-based composite material were discussed in this paper with more focus on its body armour applications. Kevlar sheets that are reinforced with varieties of natural fibres in different alignments in a polymer matrix have been studied extensively during recent times. The high specific strength of such fibres positively contributes to the overall mechanical properties of the composite material, and the characterisation of the post-impact bulletproof structure can reveal the vital mechanisms of failure. This can result in optimum arrangements of ply angle and orientation of the natural fibres and Kevlar sheets for better durability. However, there is still need for future research to focus more on the development of Kevlar fibres impregnated between composite plates for the development of body armour. New backup materials need to be explored to study the impact of different types of bullets on the vest material with Kevlar, which provides a network structure for arresting the bullet, thereby safeguarding the user. Hence, the design of experiments is very important in further research, so that the type of bullet for the newly developed material can be clearly defined and applied for specific environments. Furthermore, the optimisation of fibre material in view of how much weight percentage it should have in a polymer matrix governs the strength of the material. The aim of the researcher should be to reduce weight without compromising other desired properties, such as tensile strength, impact strength, energy absorption and fire resistance. Hence, it can be concluded that the applications of Kevlar-based composite structures must be explored extensively, not only in ballistic but also in automobile, aerospace, domestic and medical applications.

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