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Influence of Fiber Fillers on The Ballistic Properties of Epoxy and Polyester Resins: A Review

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Abstract:
Ballistic shields are considered a tactical measure to protect high-risk areas. Due to their advanced design, they provide effective protection against fragments and projectiles, reducing fatalities and preserving lives under adverse conditions. Therefore, researchers have focused on the importance of materials in the production of these shields, emphasizing three main aspects: lightweight properties, cost, and ballistic resistance. They have used polymeric materials reinforced with fillers to enhance ballistic resistance, competing with metal and ceramic shields. The present research has examined studies involving epoxy and polyester as core materials, and Kevlar, natural fibers, carbon fibers, and carbon nanofibers as reinforcements. Comprehensive research indicated that Kevlar-reinforced epoxy resins enhance impact resistance, energy absorption, and ballistic resistance; the research has achieved improved results in configurations of 4 to 10 layers or 6 to 22 layers when combined with rubber or alumina additives. Polyester resin composites provide excellent impact resistance, especially when combined with 20–33 layers of Kevlar; however, some natural fibers offer enhanced multi-impact resistance and ballistic protection compared to standard Kevlar. The mechanical and ballistic properties of epoxy and polyester resins are significantly enhanced by incorporating carbon fiber and carbon nanotube (CNT) reinforcements. CNT additions to epoxy resins have been shown to enhance dynamic properties and energy absorption; at a 4% CNT concentration, the intensity of the shock wave can be reduced by up to 33%. CNTs at a 1% concentration produce optimal energy absorption. In contrast, ramie fibers outperform Kevlar in terms of cost-effectiveness and weight, achieving cost reductions of up to 95% and enhancing scratch depth resistance through additional layers of reinforcement. Sisal, jute, and other natural fibers provide cost-effective alternatives to Kevlar.

Keywords:
Epoxy resin; Ballistic impact; Armors; Kevlar; Natural fibers.

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Highlights:

- Polymer composites offer enhanced toughness and impact resistance.
- Body armor evolution focuses on weight reduction and absorption improvements.
- Kevlar and natural fibers show promise in ballistics.

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1.INTRODUCTION

Armor designers and body armor users commonly strive to balance the weight, thickness, and cost of the armor package, considering the specific threat level it is intended to protect against. An armored structural composite is a novel armor material used in armored weapon systems, valued for its exceptional load-bearing, ballistic, and absorption characteristics [1]. Body armor has proven highly beneficial in combat scenarios requiring high ballistic protection. The development of body armor has progressed in tandem with technological advancements, aiming to minimize casualties from bullet contact, enhance energy absorption, and reduce overall weight [2, 3]. Body armor can be classified into two main types: soft and hard. Soft armor consists of numerous layers of textiles, typically 20 to 50 layers, and weighs 4.5 kg. Soft armor is precisely engineered to protect against low to medium-energy assaults, with velocities of up to 500 m/s, as outlined by the armor standard set by the National Institute of Justice NIJ. Conversely, hard armor was explicitly designed to withstand bullet speeds of NIJ class IIIA or higher, i.e., greater than 500 m/s, when worn alongside a soft armor vest [4, 5]. Integral armor systems represent a cutting-edge development in lightweight armor. The most effective armors consist of multiple layers of diverse materials arranged in a sequence rather than being made of a single substance, such as steel, composites, or ceramics. Research is underway to produce advanced armor materials that protect against devastating weaponry [6, 7]. The aim of this research is to study the effect of different types of fibers, e.g., Kevlar, natural fibers, carbon, or aramid, on the mechanical and ballistic properties of two common polymeric materials, epoxy and polyester, with the aim of improving their performance under ballistic impact. The research aims to identify the optimal types of fibers that enhance strength and stiffness, with a focus on energy distribution and delaying material failure during impact, which will contribute to the development of more efficient composite materials for defense and security applications such as body armor and impact-resistant structures, through a comprehensive review of previous research.

2.ARMOR MATERIALS WITH DIFFERENT INGREDIENTS

2.1.Armor Composed of Metal and Alloy Matrices

Metal matrix composites MMCs have been intensively researched because of their exceptional qualities, such as simultaneous high strength and lightweight, resulting from combining different elements. They have been extensively used across several industries, such as industrial, aircraft, transportation, and armor. Following iron and steel, aluminum alloys are the second-most-used metals owing to their favorable mechanical properties [8]. The use of aluminum alloy armor started in the mid-20th century. Thus far, it has progressed through four stages: starting with high-toughness weldable armor made of Al-Mg alloy, then advancing to "Middle-toughness weldable armor of Al-Zn-Mg alloy," followed by "Aluminum-alloy gap laminated armor," and finally, Aluminum-alloy armor connected with compound armor [9]. Armored vehicles equipped with aluminum armor typically weigh 20% less than those with steel armor. Additionally, the bending stiffness of aluminum armor is nine times greater than that of steel armor of equivalent weight. Consequently, aluminum armor has gained widespread [9, 10].

2.2.Armor Materials Composed of Ceramic Matrices

Ceramic Matrix Composites CMCs possess many notable characteristics. Ceramic materials have emerged as a promising anti-ballistic material owing to their low density, high hardness, and exceptional compressive strength [11]. The development of ceramic armor has seen significant advancements, including the incorporation of perforated or multipiece ceramic components, the choice of whether to encapsulate them in metals or cermet, the use of effective methods for combining ceramic pieces at low temperatures to achieve high-performance ceramic bonds, and the implementation of functional gradation of microstructures, among other possibilities [12]. Integrating ceramic composites with enhanced mechanical properties into lightweight ceramic armor is crucial and depends on several factors. The assessment of ceramic armors should include several factors, including ballistic energy dispersion, physical characteristics, streamlined production, and microstructure [12, 13].

2.3.Armor Materials Composed of Polymer Matrices

Polymer matrix composites consist of a polymer matrix phase often reinforced with organic or inorganic fibers. Composite materials, especially polymer fiber composites, are becoming increasingly popular in many industrial sectors. These composites have superior mechanical and thermal strength and low specific gravity [14]. Polymer composites have seen great demand due to their favorable weight-to-strength ratio. They are widely used in many industrial applications. However, the fire-resistant properties of these polymer composites have led to significant safety concerns throughout their service life. During the operational life of aerospace structures, ships, power transmission systems, and vehicles, foreign objects may generate ballistic impact loads from bird strikes, hail, shrapnel, runway debris, bullets, and explosive fragments [15]. In addition to the possibility of penetration, these impacts may cause significant detachment, leading to deterioration of structural performance. Most of these structures are not designed to serve as armored forces. Therefore, it is necessary to evaluate their ability to withstand high-velocity impacts from poor-quality parts. To fully understand their response to projectiles, it is necessary to study the effects of impact loads and the damage processes they induce [15, 16]. Armor designers were initially drawn to ceramics for their exceptional mechanical properties, including high hardness, high compressive strength, and low density. Modern armor design often includes an integral two-layer armor consisting of a ceramic front layer and a tensile back layer [17]. Modern armor effectively protects against high-velocity impacts but is less effective at dispersing the energy from shock waves generated by explosions. Fiber-reinforced polymer composites have been used to effectively reduce the weight of body armor and enhance the troops' mobility. There is a growing global interest in creating a lighter, stronger material capable of protecting against high-velocity projectiles. Kevlar fibers are the most popular of these reinforcements due to their exceptional strength-to-weight ratio, relatively affordable cost, and remarkable durability. Kevlar is well-suited for use in bulletproof vests, integral helmets, and fabric breadboards for transportation and military vehicles. Therefore, metal alloys and ceramics are being replaced by polymer composites to achieve greater cost efficiency in manufacturing [18, 19]. Armor is essential for safeguarding both life and property. However, with the vast array of materials at one's disposal, selecting the appropriate one can be perplexing. Thankfully, the three primary competitors in the arena are polymer, ceramic, and metal. Each has distinct advantages and disadvantages, making them appropriate for different purposes. The weight and cost of armor are crucial attribute that directly impacts mobility and comfort during use. Research has focused on developing lightweight armor made from polymeric materials as an alternative to heavy ceramic and metal components. By conducting the study, these entities can be compared based on their weights and costs, as shown in Figs. 1 and 2.

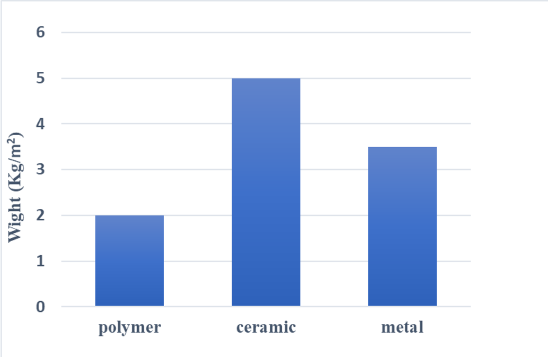

Fig. 1 Weight Comparison of Armor Basic Materials(kg/m²) [20].

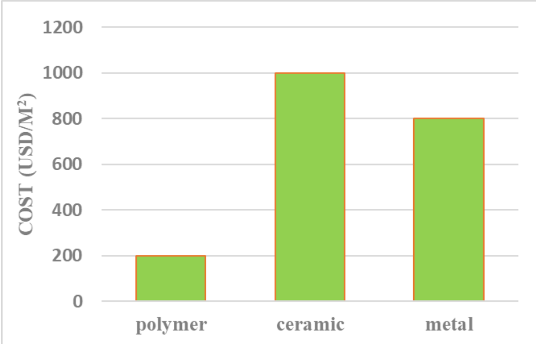

Fig. 2 Comparison by Cost (USD/m²) [20].

Epoxy and polyester resins have exceptional properties, such as low cost, good mechanical strength and toughness, low curing shrinkage, improved adhesion, high compatibility with a wide range of materials, and electrical insulation [21]. Epoxy and polyester resins are widely used as corrosion- and chemical-resistant materials, and their compounds are widely used in many industries due to their exceptional properties, achieved through various formulations and specialized curing agents [22, 23].

3.BALLISTICS TEST

Ballistic impact testing is an essential method for evaluating a material's ability to withstand high-speed projectile impacts. It is crucial in several domains, including the advancement of body armor, the design of armored vehicles, and aeronautical engineering. The experiment involves launching a projectile, such as a bullet or fragment, at a target material in a controlled environment. The velocity at which the projectile hits, the qualities of the materials involved, and the shape of the target are closely observed and studied to assess the damage caused. Figure 3 shows a schematic view of the ballistic test system [24, 25].

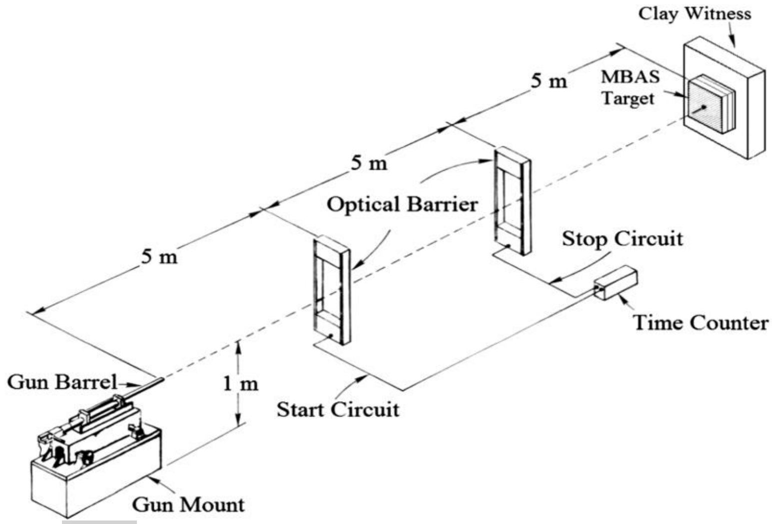

Fig. 3 Schematic View of the Ballistic Test System [26].

4.FIBERS USED FOR ENFORCEMENT

4.1.Kevlar Fibers

Due to its high modulus, increased strength-to-weight ratio, and high failure strain, Kevlar-based unidirectional composites are frequently utilized as body armor materials; Kevlar grade levels are [27, 28]:

- Kevlar K-29 is used in replacement and body/vehicle armor.
- High-modulus Kevlar K49 is utilized in rope and cable products.
- Kevlar K100 is a colored variant of Kevlar used in industrial applications, including cables and brakes.
- Kevlar K119: more elastic, fatigue-resistant, and with higher elongation.
- Greater toughness for ballistic applications with Kevlar K129 linings and asbestos.
- Kevlar AP is 15% stronger than K-29 in tensile strength.
- Kevlar XP combines KM2 plus fiber with a lighter resin.
- Kevlar KM2: improved ballistic resistance for use in armor.

Table 1 shows the effect of Kevlar fibers on armor composite properties. Depending on the materials and techniques used, the effects of Kevlar, Ramie, CNT, and glass fibers on the ballistic properties of epoxy and polyester resins show different improvements. Kevlar-reinforced epoxy resins often increase impact tolerance, energy absorption, and ballistic resistance. The best results are obtained with designs containing 4–10 or 6–22 layers, in conjunction with rubber or AlO_3 additives. Similarly, polyester resin composites improve mechanical properties such as tensile strength and natural frequency by providing substantial impact resistance, especially when combined with 20–33 Kevlar layers or hybrid reinforcements comprising carbon fibers and MWCNT. Ramie fibers outperformed Kevlar in energy absorption and cost-effectiveness, delivering up to 95% cost savings while improving indentation resistance. With additional reinforcing layers, glass fibers also showed improved mechanical properties, such as tensile strength and hardness. Certain layers and hybrid stacking, such as Kevlar/aluminum laminate, produced notable ballistic enhancements, while nano-clay and nano-calcite additions further enhanced impact resistance in Kevlar-epoxy systems. These cutting-edge materials, reinforced polyester and epoxy resins, provide customized solutions for impact-resistant systems and body armor.

4.2.Natural Fibers

The use of “green” materials to replace synthetic materials has gained significant traction in recent decades. Green materials are environmentally friendly for sustainable reasons related to their renewable and biodegradable properties. In this regard, the superior technological performance of natural plant-derived lignocellulosic fibers as reinforcement for polymeric composites has attracted attention, in addition to their sustainable benefits. The search parameters include cross-referencing using the search term “fiber name” for the composite and the title or keyword “fiber name”, including name variants [33, 42]. Table 2 shows the effect of natural fibers on armor properties.

Table 1 Effect of Kevlar Fibers on the Properties of the Armor Composite.

Type of material of enforcement	Percent of addition	Properties enhanced	Method of forming or enforcement	Refs.
Epoxy resin	4,6,8,10 layers of Kevlar-29 + Al2O3 powder	Increasing thickness increases ballistic velocity, energy absorption, and residual velocity with increasing initial velocity, but tensile strength decreases.	Hand-layup	[29]
Polyester resin	22,28,33 layers of Kevlar	A 20 mm-thick composite panel had the highest impact resistance.	Hand-layup	[30]
Epoxy resin hardener type CY1300/HY 956	6,14, 22 layers of Kevlar-29 + Al2O3 powder	A 12 mm-thick composite plate is suitable for impacts up to 200 m/s.	Hand-layup	[31]
Polyester resin	6,14,22 kevlar-29	The 12 mm thickness is the most effective in resisting impact loads.	Hand-layup	[32]
Epoxy resin/hardener type 506/HY 956	6,14, 22 layers of Kevlar-29 + 6061-T6 aluminum laminate	The composites' energy absorption increased with the starting velocity.	Hand-layup	[33]
polyester resin	20 layers of Kevlar-29	The composite can endure the impact energy. Reduction of 63.8% in the expenses associated with localizing the manufacture of body armor.	Hand-layup	[34]
Epoxy resin (DGEBA)/(TETA) as hardener)	18 plies of Kevlar or 30 vol.% ramie fibers	The ramie composite exhibited indentation depths 10-20% lower than those of Kevlar. The ramie composite absorbed three times as much energy as Kevlar and achieved a 95% cost reduction.	Hand-layup	[26]
The epoxy resin was loaded with 1 wt.% and 2 wt.% of nano-clay and nano-calcite.	20 plies of Kevlar fibers	Adding tiny quantities of nano clay and nano calcite enhanced impact resistance, with 1% nano clay and 2% nano calcite demonstrating the most effective results.	Hand-layup	[35]
Epoxy resin LY 564 with Aradur 22962 as the hardener	Pure Kevlar-29 or Kevlar-29 +	Adding rubber improves impact resistance and reduces blunt damage. Adding more rubber to the matrix weakens the bonding between Kevlar layers. The optimal rubber-to-epoxy ratio is 12.5%.	Hand-layup	[36]
Epoxy resin (DGEBA)/(TETA) as hardener)	30 vol.% ramie fiber or 30vol% aramid fiber or Kevlar fiber	The ramie fiber composite MAS was the most cost-effective choice.	Cavity steel mold with pressure	[37]
Polyester resin	0.4wt% MWCNT, Kevlar, carbon fiber	The nanocomposite with the stacking sequence (UP + K/K/K + MWCNT) exhibited a natural frequency of about 10.4% higher than other composites. The nanohybrid materials (UP + K/C/K + MWCNT) and (UP + C/K/C + MWCNT) exhibited increases of 13.82% and 5.8% in natural frequency, respectively.	Hand-layup	[38]
Epoxy resin	8 layers of Kevlar	Exceptional bullet resistance was achieved with a robust backing material, such as aluminum oxide ceramic.	Hand-layup	[39]
Epoxy 105 /207 Hardener	16 layers of Kevlar-29	The cover layer improves the ballistic resistance of the armor system.	Hand-layup	[40]
Epoxy 105 / 207 Harender	A single ply of Kevlar-29 or A single ply of Dyneema fibers consists of four layers of unidirectional fibers aligned in a sequence of 0°/90°/0°/90°	Kevlar-29/epoxy-reinforced armor had a lower penetration speed than UHMWPE fiber-reinforced armor.	Hand-layup	[41]

Table 2 Effect of Natural Fibers on the Properties of the Armor Composite.

Type of material of enforcement	Percent of addition	Properties enhanced	Method of forming or enforcement	Refs.
Epoxy resin (DGEBA)/(TETA) as hardener)	30 vol.% sisal fibers or 16 plies of aramid fiber	Superior ballistic performance compared to the aramid fabric, with a 20% increase,5% lighter, and 31% more cost-effective.	Hand-layup	[43]
Epoxy resin (DGEBA)/(TETA) as hardener)	30 vol.% jute fibers or 16 plies of Kevlar fibers	Kevlar fabric showed the greatest penetration depth, followed by jute fabric. Significant cost savings compared to aramid fabric (44%) and standard epoxy (14%).	Hand-layup	[44]
Polyester resin	10, 20, and 30 vol.% curaua fiber/ 16 ply of aramid	The curaua fiber composite with a 30% composition exhibited intriguing characteristics suitable for multi-impact uses, including exceptional energy absorption and commendable post-impact cohesiveness.	Hand-layup	[44]
Epoxy resin (DGEBA)/(TETA) as hardener)	10, 20, and 30 vol.% coir fibers	The 30% coconut fiber composites provided ballistic protection similar to Kevlar.	Hand-layup	[45]
Epoxy resin (DGEBA)/(TETA) as hardener)	30 vol.% mallow fibers	The mallow fiber composite offers cost savings and a slight increase in weight, making it a viable alternative to Kevlar in personal protective armor applications.	Hand-layup	[46]
Polyester resin	30 vol.% jute nonwoven mat	The aramid fabric with a polyester matrix, bound with a jute nonwoven mat, results in a 5.4% weight reduction and an impressive 474% cost reduction.	Hand-layup	[53]
Epoxy resin (DGEBA)/(TETA) as hardener)	10%, 20%, 30%, 40%, and 50 vol.% of piassava fibers	The composite of 50% Biasava fibers arranged in a crisscross pattern exhibited resilience against ballistic impact.	Hand-layup	[47]
Polyester resin	10, 20, and 30 vol.% Fique fibers, 10, 20, and 30 vol.% fabric	The ballistic performance of fibers and fabric fibers reinforced with polyester compounds has been improved by 10%.	compression molding	[61]
Epoxy resin (DGEBA)/(TETA) as hardener)	30 vol.% of Pineapple Leaf or ultra-high-molecular-weight polyethylene (UHMWPE, Dyneema fibers	Tests with single-layer ceramic armor plates demonstrated a 35% augmentation in BFS depth. The PALF composite demonstrated exceptional ballistic performance.	compression molding	[48]
Epoxy resin (DGEBA)/(TETA) as hardener)	15,30,40,50 vol% Fique fibers	The composite of 15 to 50% fibrous tissue exhibited comparable energy absorption and restricted velocities, offering superior ballistic protection compared to pure epoxy and Kevlar.	Hand-layup	[49]
Epoxy resin (DGEBA)/(TETA) as hardener)	30 vol.% of Garuman fibers	Long Guruman fibers, organized in a crisscross pattern ranging from 0 to 90°, showed a BFS in the clay below the 44 mm threshold.	Hand-layup	[50]
Epoxy resin (DGEBA)/(TETA) as hardener)	buriti fabric at volume fractions of 10%, 20%, and 30%	The composites with 10% and 20% showed structural failure when subjected to impact.	Hand-layup	[51]
Epoxy resin (DGEBA)/(TETA) as hardener)	20%,30%,40 vol% kenaf fibers	A substantial increase in strength, exceeding 600%.	Hand-layup	[52]
Epoxy resin (DGEBA)/(TETA) as hardener)	10, 20, 30, and 40 vol.% of Titica Vine fibers	The composites exhibited a rear BFS depth of less than 44 mm. The specimens with 20% TVF content absorbed more impact energy than those with 40% TVF content.	Hand-layup	[53]

In addition to providing cost and weight benefits, natural fibers, including sisal, jute, mallow, curaua, coir, fique, and kenaf, significantly enhance the ballistic performance of epoxy and polyester resins. While curaua, coir, and fique fibers provide superior multi-impact resistance and ballistic protection, composites including fibers like sisal and mallow are more cost-effective and better at energy absorption than regular Kevlar. Fibers from kenaf and pineapple leaf (PALF) provide remarkable strength and depth reduction in backface ballistic applications thanks to hybrid designs that further lower costs and improve performance, such as aramid-jute or fabric reinforcements.

4.3.Carbon Fibers

Carbon fiber-reinforced polymer (CFRP) composites have become a favored material in several industries during the last few decades, surpassing conventional materials. The rising popularity is attributed to its exceptional characteristics, such as its lightweight design, high specific strength, and high specific modulus. Carbon materials are vital as structural components in aircraft, transportation, architecture, communication, and lighting. Carbon fibers offer exceptional performance characteristics and cost-effective properties that enhance several developing applications [54, 55]. Table 3 shows the effect of the carbon fibers on the armor composite properties. Figure 4 shows worldwide carbon fiber demand by application.

Table 3 Effect of Carbon Fibers on the Properties of the Armor Composite.

Type of material of enforcement	Percent of addition	Properties enhanced	Method of forming or enforcement	Refs.
Epoxy resin	Carbon fiber	The carbon/epoxy composite exhibits excellent impact resistance and extraordinary energy absorption capabilities when subjected to high-velocity impacts, surpassing that of steel structures.	Simulation models	[56]
Epoxy resin TDE-86	12K T700, 3K T300 carbon fibers	The investigation revealed a positive relationship between accident speed and the energy absorption of 3D-braided carbon fiber-reinforced carbon fiber.	3D DIC technique	[57]
Epoxy resin CYCOM PR 520	2D, 3D Carbon fiber	Carbon fiber composites perform worse in ballistic impact scenarios than materials like Kevlar or polyethylene composites.	Hand-layup	[58]
Epoxy resins	95 plies carbon fiber	Exceptional compressive strength enables the creation of a protective layer that serves as a viable substitute for armor.	Hand-layup	[59]
Epoxy resin	4 plies of carbon fibers	Panels with alternating layers of 0° or 90° angle and 45° or -45° rotation absorb more energy than other panel designs. Laminated variants E [45/ 45/ 90/ 0] and E1 [45/ 45/ 0/ 90] have the lowest puncture energy among all other configurations.	Hand-layup	[54]
Epoxy resin	2,46,48 plies T700 carbon fiber	Significant improvement in its ability to withstand ballistic forces. Increasing the thickness of the polyurea layer on the posterior side enhances the composite construction's energy absorption.	Polyurea spraying method	[60]
Epoxy resin	14 plies of carbon fibers	The composite material, which is 4.2mm thick and consists of 14 layers of carbon fiber and epoxy, can withstand bullet penetration.	Molding method	[61]

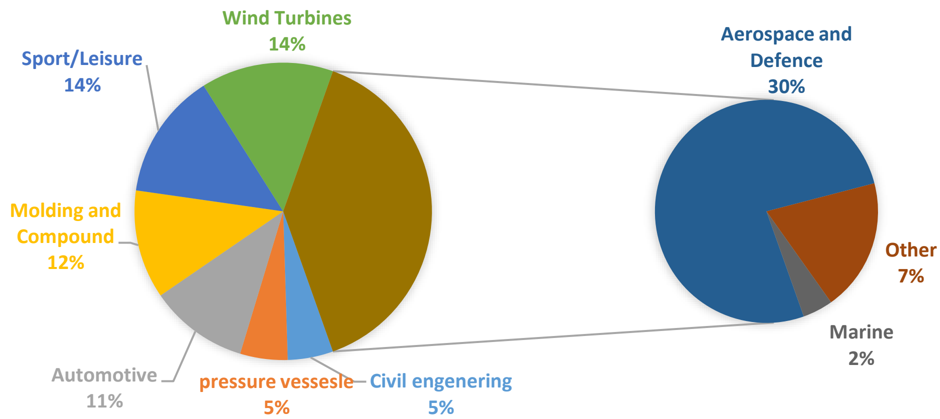

Fig. 4 Worldwide Carbon Fiber Demand by Application in Thousands of Metric Tons [62].

4.4.Carbon Nanotube Fiber

Carbon nanotubes (CNTs) have generated significant interest in many scientific and engineering disciplines due to their exceptional physical and chemical properties. Small and nanosized particles are used as fillers for polymers to create high-potential composites with enhanced properties. Carbon nanotubes are a type of one-dimensional carbon material with an aspect ratio exceeding 1000, in contrast to other carbon materials, including diamond, graphite, and fullerene [63, 64]. A carbon nanotube (CNT) is a very small, lightweight nanotube; however, it has been described as 100 times stronger than steel. The unique strength comes from the covalent connections within the carbon molecules in a single cylinder. Various methods have been developed to integrate carbon nanotubes into polymer matrices, yielding novel materials with various properties. Some methods aim to transfer the distinctive electrical properties of carbon nanotubes into insulating polymer matrices to enhance the conductivity of polymer composites [65, 66]. Table 4 shows the effect of carbon nanotubes on the composite's properties.

Table 4 Effect of Carbon Nanotube Fibers on the Properties of the Armor Composite.

Type of material of enforcement	Percent of addition	Properties enhanced	Method of forming or enforcement	Ref.
Epoxy resin	MWCNTS, E-glass, Kevlar-29	A 6.5% enhancement in the ballistic test.	Hand-layup	[67]
Epoxy resin Epon 862	(0%, 0.5%, 1%, 2%, and 4 wt.%) of carbon nanotubes	A significant increase in the energy absorption capacity of textile composites and an improvement in their dynamic properties by up to 13% with the addition of 1% CNT.	Hand-layup	[68]
Epoxy resin RESOLTECH Resin HTG 210 and Hardener HTG 216	(0%, 1%, 2%, and 4wt%) of carbon nanotubes	The inclusion of CNTs with a mass fraction of 4% resulted in a 33.34% reduction in shock wave intensity compared to composites without CNTs.	sonication, mechanical and magnetic stirring, high-speed shear mixing methods	[63]
Polyester resin	0.4wt% MWCNT, Kevlar, carbon fiber	The hybrid nanocomposite with the stacking sequence (UP + K/K/K + MWCNT) exhibited a natural frequency of about 10.4% higher than other composites.	Hand-layup	[38]

The mechanical and ballistic properties of epoxy and polyester resins are significantly improved by the addition of carbon fiber and carbon nanotube (CNT) reinforcements. Carbon fiber composites are good alternatives to armor and protective layers due to their superior compressive strength, energy absorption, and impact resistance. Energy absorption is maximized by certain configurations, such as alternate ply orientations or 3D-braided carbon fibers, and ballistic performance is further enhanced by increasing thickness, such as polyurea layers. CNT additions to epoxy resins improve dynamic characteristics and energy absorption; at 4% CNT content, shock wave intensity may be reduced by up to 33%. With 1% CNT providing the most energy absorption, hybrid composites including carbon, Kevlar, and carbon fibers increase natural frequencies and ballistic performance. These materials provide cutting-edge solutions for applications that require high performance and impact resistance.

5.CONCLUSIONS

The ballistic and mechanical properties of epoxy and polyester resins are significantly enhanced by advanced reinforcements, including Kevlar, Ramie, glass fibers, carbon fibers, and carbon nanotubes. When combined with additives like rubber, Al_2O_3, or nanoparticles, Kevlar-based composites, especially in hybrid and multilayer forms, exhibit remarkable energy absorption, impact resistance, and ballistic performance. By using hybrid reinforcements, polyester resins also attain greater frequency and tensile strength. Ramie, sisal, jute, and other natural fibers provide affordable, sustainable substitutes for Kevlar, and many outperform it in some impact characteristics, such as BFS reduction and indentation resistance. Strength, energy absorption, and dynamic performance are further enhanced by glass fibers and carbon fiber-CNT hybrids, making them perfect for high-performance applications such as protection systems and body armor. These developments provide a customized strategy for achieving greater ballistic protection while reducing weight and cost in composite materials.

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