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Fiber Reinforced Composites - A Review

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Abstract

Fiber-reinforced composites are essentially axial particulates embedded in fitting matrices. The primary objective of fiber-reinforced composites it to obtain materials with high strength in conjunction with higher elastic modulus. The strength elevation is however affected with applied load transiting from matrix to fibers, interfacial bonding between fiber-matrix, their relative alignment and nature of fiber scheming the overall material behaviors. The alignment of fibers may however be continuous or random depending on the end applications. The choice of the fiber reinforcement and its fitting matrix also depends on application requirements. In recent years, the advent of composite technology has led to the development of different fiber reinforced composite systems via varying manufacturing methodologies to obtain advanced material behaviors. Herein, we present a comparative account on various kinds of synthetic fibers and their significance as potential reinforcements with special emphasis on carbon fibers.

Keywords: Fibers; E-glass; Carbon; Kevlar; Low elastic modulus (LM)

Introduction

Composite materials are considered as one of the most potential candidates for aerospace applications owing to their high strength-to-weight ratio and excellent fatigue resistance [1,2]. Polymer based composite systems offer multiple functionalities, owing to the synergistic combination of functional fillers with highly process able polymers, which in-turn widens their application window [3,4]. In general, composite materials employed for structural applications are best classified as high performance systems and are made of synthetic materials that offer high strength-to-weight ratios, but often demands controlled manufacturing environments for optimum performance. Fiber reinforced polymers are also known for their potential as high-tech, high-quality materials in electrical as well as military applications. Although, the applications of fiber reinforced plastics are still limited to smaller parts made of reinforced plastics, such as parts of the bridge deck, girders, reinforcement bars, staying cables or handrails [5-11]. In recent years, reinforced plastics are also established to be well drafted for building and construction, in addition to transport and electronic applications. Some of the major application areas of Fiber Reinforced Plastics (FRP) in transportation are automotive, aviation, shipping and other related sectors. In energy/electronic sector, FRP are employed towards the fabrication of high voltage switches, cryostats, dry transformers and many more. Lately, carbon fiber reinforced polymers are also used for advanced technical applications such as in rocket nozzles. The pie chart below gives a detailed picture of market shares of FRPs in various application areas [12-14] (Figure 1).

The reinforcement of fiber upon polymeric matrix is found to bring about significant advancements in mechanical behaviors of polymeric host with added advantages of light weight, high strength to weight ratio, excellent weathering stabilities and enhanced dimensional stabilities [15], in addition to low maintenance cost and tailor made material behaviors. However, to obtain tailor made properties that suit specified application requirements, various types of fibers with varying polymers have been tried, with fibers contributing towards the betterment of mechanical, tribological, thermal and water sorption behaviours of resulting composites. Nevertheless, one could expect herculean results, when the fibers are of near-to-infinite length, isotropic and are inserted unidirectional. Conversely, the greater anisotropic and shorter their length of fibers, lower would be their overall mechanical performance. The observed large leeway regarding length, direction and type of fiber widens the application window of FRP composites. Further, the composite can be completely tailor made to suit specific mechanical needs for any given project, which in turn aids far better efficiency towards end applications. The most common fibers exercised in recent times are glass fibers, carbon fibers, aramid fibers and natural fibers, next to which are the nylon-and polyester fibers. All these reinforcements are ideally less dense and hence present

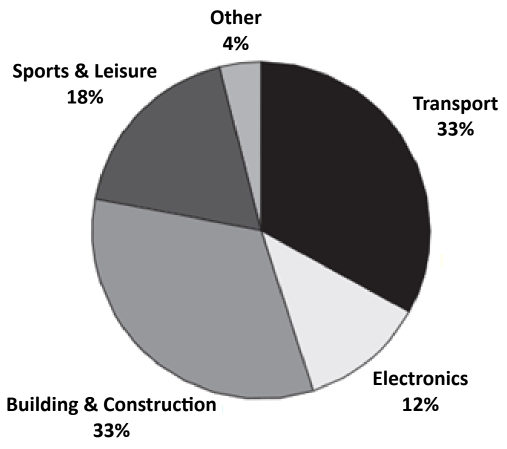

Figure 1: A pictorial representation of market shares of FRPs.

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the matrix with a higher strength and stiffness. The excellent strength/stiffness to weight ratio of composites is however credited to low fiber densities. Nevertheless, all fibers behave quasi-elastically until breakage, with carbon fibers much stiffer and lighter that glass fibers. This in turn, accounts for their increased preference for many high performance applications.

Important Types of Fiber Reinforcements

Glass fibers

The mechanical behaviours of fiber-reinforced composites are primarily dependent on their inherent abilities to enable stress transfer, which in turn depends on the fiber strength, matrix strength and the strength of interfacial adhesion between the fiber/matrix [16]. Glass fibers (GFs) have been employed in various forms such as longitudinal, woven mat, chopped fiber (distinct) and chopped mats to enhance the mechanical and tribological properties of the fiber reinforced composites. The properties of such composites was however dependent on the nature and orientation of the fibers laid during composite preparation [17]. Glass fibers are one of the most widely used polymer reinforcements with nearly 90% of all FRPs made of glass fibers. Of which, the oldest and the most popular form is the E-glass or electrical grade glass. Other types of glass fibers include A-glass or alkali glass, C-glass or chemical resistant glass, and the high strength R-glass and/or S-glass. Under laboratory circumstances glass fibers can resist tensile stresses of about 7000 N/mm^2, whereas commercial glass fibers reach 2800 to 4800 N/mm^2 [18] (Figure 2).

(a) (b)

Figure 2: Digital images of (a) Unwound glass fibers; (b) Woven glass fiber.

Classes of GFs	Physical properties
A glass	High durability, strength and electrical resistivity
C glass	High corrosion resistance
D glass	Low dielectric constant
E glass	Higher strength and electrical resistivity
AR glass	Alkali resistance
R glass	Higher strength and acid corrosion resistance
S glass	Higher tensile strength

Table 1: Physical properties of various classes of glass fibers.

Classification of glass fibers: The major classes of GFs and their inherent physical properties are depicted in Table 1 [19], while their chemical composition is tabulated in Table 2. The physical and mechanical properties of different classes of GFs are shown in Table 3.

Various commercially imperative products have been developed using glass fibers. Each of which defer in its overall material performance. Table 4 summarises the mechanical properties of various glass fibre products.

Carbon fibers

Carbon fibers (GFs) are the new breed of high strength materials made of graphitic and non-crystalline regions. Of all reinforcing fibers, carbon fibers offer the highest specific modulus and strength. Additionally, carbon fibers have the ability to retain its tensile strength even at high temperatures and are independent of moisture. Carbon fibers do not necessarily break under stress in contrast to glass and other organic polymer fibers [20]. Carbon fibres also offer high electrical and thermal conductivities with relatively low coefficient of thermal expansion [21-24]. This innate property of carbon fibers makes them ideal for applications in aerospace, electronics and automobile sectors. The carbon fibers offer a maximum strength of 7Gpa, axial compressive strength is 10-60% of their tensile strength [25,26] and transverse compressive strength is 12-20% of their axial compressive strength [27]. Poly-acrylonitrile (PAN) is one of the most common precursors employed in carbon fiber production, which offers high tensile strength and higher elastic modulus, extensively applied for structural material composites in aerospace and sporting/recreational goods. Depending on the final curing temperature, different classes of carbon fibers namely high tenacity (HT) fibers, intermediate modulus (IM) fibers, high modulus (HM) fibers and ultra-high modulus (UHM) fibers are formed with PAN precursors. Another production technique, takes advantage of petroleum-pitch (PP) as precursors. These types of carbon fiber have a higher E-modulus and lower tensile strength and are extensively adopted in high stiffness components that utilize high thermal and electrical conductivities [28] (Figure 3).

Characteristics of carbon fibers: Carbon fibers are very versatile, because of their extremely high strength to weight and stiffness to weight ratios. Moreover, they are chemically inert, electrically conductive and infusible. The stiffness and modulus of elasticity of carbon fibers can range from glass to three times that of steel. The most widely used types have a modulus of 200.000-400.000 N/mm^2. Table 5 gives a detailed representation of mechanical behaviours of various carbon fiber products.

Carbon fibers may either be directly processed as finished product or as pre-product. Finished products may appear as woven tubes or pultruded sections. While, pre-products may include short fibers, twisted or non-twisted yarns, continuous filament, tows and so forth. Table 6 gives a detailed picture of important types of commercially important carbon fiber tows, with a comparative view of its physico-mechanical behaviours.

Type of GF	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	B_2O_3	CaO	MgO	Na_2O	K_2O
E-glass	55	14	-	0.2	7	22	1	0.5	0.3
C-glass	64.6	4.1	-	-	5	13.4	3.3	9.6	0.5
S-glass	65	25	-	-	-	-	10	-	-
A-glass	67.5	3.5	-	-	1.5	6.5	4.5	13.5	3
R-glass	60	-	-	-	-	9	6	0.5	0.1
EC-Glass	58	12.4		-	-	23		-	-
AR-glass	61	1	-	-	-	5	1	14	3

Table 2: Chemical compositions (wt %) of glass fiber types.

Type	Density (g/ cm^3)	Tensile strength GPa	Young's modulus (GPa)	Elongation (%)	Coefficient of thermal expansion (10^{-7}/°C)	Poison's ratio	Refractive index
E-glass	2.58	3.445	72.3	4.8	54	0.2	1.558
C-glass	2.52	3.310	68.9	4.8	63	-	1.533
S-glass	2.46	4.890	86.9	5.7	16	0.22	1.521
A-glass	2.44	3.310	68.9	4.8	73	-	1.538
R-glass	2.54	4.135	85.5	4.8	33	-	1.546
EC-Glass	2.72	3.445	85.5	4.8	59	-	1.579
AR-glass	2.70	3.241	73.1	4.4	65	-	1.562

Table 3: Physical and mechanical properties of GFs.

Types	Unit	Woven cloth	Chopped strand mat	Continuous roving
Glass content	%	55	30	70
Tensile strength	N/mm^2	300	100	800
Compressive strength	N/mm^2	250	150	350
Flexural strength	N/mm^2	400	150	1000
Flexural modulus	N/mm^2	15000	7000	40000
Impact strength	kJ/m^2	150	75	250
Coefficient of linear thermal expansion	$\times 10^{-6}$/°C	12	30	10
Thermal conductivity	W/mK	0.28	0.2	0.29

Table 4: Mechanical properties of various glassfiber products.

Types	Ultra high elastic modulus type (UHM)	High elastic modulus type (HM)	Intermediate elastic modulus type (IM)	Standard elastic modulus type (HT)	Low elastic modulus type (LM)
Tensile elastic modulus	600 GPa	350-600 GPa	280-350 GPa	200-280 GPa	200 GPa
Tensile strength	2,500 MPa	2,500 MPa	3,500 MPa	2,500 MPa	3,500 MPa

Table 5: Mechanical properties of different types of carbon fiber tows.

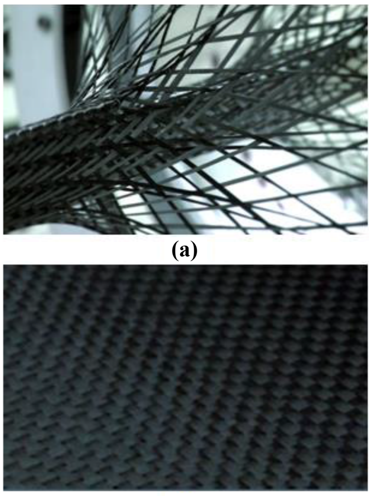

Figure 3: Digital images of (a) Unwound carbon fibers; (b) Woven carbon fiber.

Kevlar fibers

Kevlar is an aramid fiber of Poly-para-phenylen-terephtalamide (PPTA) with a rigid molecular structure. Aramid like fibers were first developed in 1960s as an alternate for steel reinforcements in rubber tyres. However, once developed the aramid fibers were also found suitable for ballistics and as surrogate for asbestos. Kevlar fibers are often used for high-performance composite applications where light weight, high strength and stiffness, damage resistance, and resistance to fatigue are of utmost importance. Aramid fibers are often employed in those applications that demands high strength and low weight together with a high impact resistance. Some of the most frequent applications of aramid materials include bullet proof vests, cooling vehicles, ship hulls and lately towards structural strengthening of civil structures.

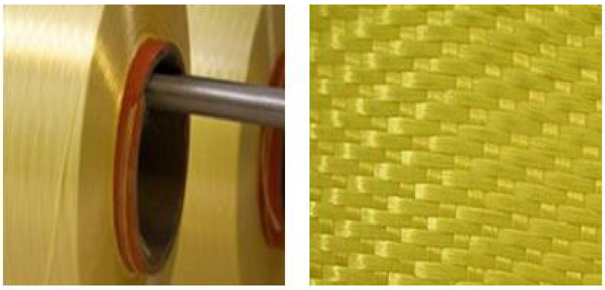

Figure 4: Digital images of (a) Unwound Kevlar fibers; (b) Woven Kevlar fibers.

Nevertheless, aramid fibers often present low compression strength. Further, the compressive modulus of aramid is of the same order as its tensile modulus [18] (Figure 4).

Types of aramid fibers: In general, aramid fibers are grouped into two categories namely,

1. Meta-aramid
2. Para-aramid

The termsmeta and para refers to the relative position of chemical bonds in the aramid fiber structure. The chemical bonds of para-aramid fibers are more aligned in the long direction of the fibers. While, the meta-aramid fibers are relatively less and/or not aligned and hence they do not they develop higher tensile strength in contrast to para-aramid bonds.

***Meta-aramids*:** Fibers made from the meta-aramid fibers often present excellent thermal, chemical and radiation resistance. They are usually employed in the fabrication of fire retardant textiles such as outer wear for fire fighters and racing car drivers. Nomex and teijiconex are well established examples of meta-aramids.

***Para-aramids*:** Fibers made of para-aramids offer higher strength. These are more commonly used in fibers reinforcement plastics for engineering structures, Stress skin panels, and other high tensile strength applications. Kevlar and Technora are commercially important para-aramid fibers [28-31]. Table 7 gives a comparative account on different grades (kevlar 29, kevlar 49, and kevlar 149) of commercially important kevlar fibers and their innate mechanical properties.

Although, aramid fibers are compatible with almost any kind of polymeric matrix. Yet, thermoplastic matrices host aramid fibers with nearly 20% more efficiency. Owing to their higher ductility, they are more compatible to aramids [16,18]. Table 8 presents a comparative view of tensile properties of epoxy composites reinforced with different types of aramid fibers.

Comparative Account of Glass, Carbon and Kevlar Fibers

Fibers in general play a crucial role in deciding the end property of the fiber reinforced composite systems. Thus, appropriate selection of fiber material and their relative orientation can lead to composite to composites with tailor made properties to suit specific application requirements. Herein, we present a comparative account of various properties of some of the technologically significant fibers (E-Glass, Low elastic modulus type carbon fiber (LM) and kevlar149), so as to ease the selection of appropriate fibers to satisfy the real time application demands. However, during, comparative studies, one has to take into account of property changes arising from difference in processing techniques, variation in precursor materials and also post-fabrication treatments, since all these factors influence the end properties of resultant fibers. E-Glass is commonly used glass fiber that offers higher strength and high electrical resistivity, LM is the type of carbon fiber with low elastic modulus, while kevlar 149 is one of aramid fibers which show significantly higher tensile strength.

Density

The density values of E-Glass, Low elastic modulus type carbon fiber (LM) and kevlar149 display significant difference. Furthermore, kevlar and carbon fibre are much lighter, while E-Glass is the heaviest (Table 9) [32-35].

Thus, carbon fiber or kevlar fibers are preferred over glass fibers in those applications that involve any structures demanding higher strength within smaller sizes.

Tensile strength

The tensile strength of glass, carbon and kevlar fibers are however similar. If tensile strength is only criteria for material selection, then cost of the material will be absolute (Table 10) [35].

Tensile modulus

All details related to Tensile Modulus mentioned in Table 11 [35].

Electrical conductivity

Carbon fibers are excellent conductors in contrast to kevlar and glass fibers. Nevertheless, kevlar is used for guy lines in transmission towers, owing to its ability to absorb water and the absorbed water conducts electricity. Since carbon fiber conducts electricity, galvanic corrosion is a concern when in contact with other metallic parts. Boaters, who have carbon fiber masts and spars, will have to insulate their aluminium fasteners and connections to avoid corrosion.

Type	Unit	55% CF SMC	Lowest grade CF epoxy fabric	Highest grade CF epoxy fabric	Carbon epoxy
Carbon fiber content	%	55	n.a	n.a	67
Density	g/cm³	1.45	1.15	1.8	n.a
Tensile strength ultimate	N/mm²	289	50	2.100	1.362
Modulus of elasticity	10³ N/mm²	55.1	6.6	520	140
Flexural yield strength	N/mm²	613	110	1600	1383
Flexural modulus	10³ N/mm²	34.5	6.410	125	122
Compressive yield strength	N/mm²	275	50	1720	1084
Compressive modulus	10³ N/mm²	31.7	8.2	140	136
Shear strength	N/mm²	65.6	0.8	120	87.4

Table 6: Comparison between three types of carbon fiber/epoxy products.

Grade	Density (g/cm³)	Tensile modulus (GPa)	Tensile strength (GPa)	Tensile elongation (%)
Kevlar 29	1.44	83	3.6	4
Kevlar 49	1.44	131	3.6-4.1	2.8
Kevlar 149	1.47	186	3.4	2

Table 7: Mechanical properties of different types of aramid fibers.

Type	Units	Aramid fiber-standard modulus-UD	Aramid fibers-high modulus-Woven
Density	g/cm³	1.31	1.27
Tensile strength	N/mm²	1400	560
Tensile modulus	10³ N/mm²	76	30

Table 8: Comparison between two aramid fiber reinforced epoxy composites.

Type of fiber	Density (g/cm³)
E glass	2.58
LM-CF	1.45
Kevlar 149	1.47

Table 9: Computed density of commercially important fibers.

Fiber	Tensile strength (GPa)
E glass	3.445
LM-CF	3.5
Kevlar 149	3.4

Table 10: Tensile strength of various types of fibers.

Fiber	Tensile modulus (GPa)
E glass	72.3
LM-CF	200
Kevlar 149	186

Table 11: Tensile modulus of various types of fibers.

Fatigue resistance

If a composite part is made to bend and straighten repeatedly, it is bound to fail due to fatigue. However, when reinforced with carbon fibers is somewhat sensitive to fatigue and tends to fail catastrophically without showing many signs of distress, while kevlar is more resistant to fatigue. Glass is somewhere in between and can be quite fatigue resistant depending on the type of glass and the setup conditions.

Abrasion resistance

Kevlar has a strong abrasion resistance, which makes it difficult to cut. One of the common applications of kevlar is as a protective glove, while using sharp blades. Carbon fiber and glass fiber have less abrasion resistant.

Chemical resistance

Aramids are sensitive to strong acids, bases, and some oxidizers, such as the chlorine bleach. Carbon fiber is however more stable and is not sensitive to chemical degradation.

Conclusion

The rationale of the presented review is to focus on the importance and inherent properties of various types of fibers. Accordingly, three synthetic fibers such as glass fiber, carbon fiber and kevlar fiber are presented, as they are the most regularly employed fiber reinforcements. Each fiber is unique in their manufacturing methods, types and properties. Further, the property of the fiber also varies with their manufacturing methods and types.

Herein, we presented a detailed tabulation of fiber types and their inherent properties, with special emphasis on their mechanical behaviors. For better understanding and easy selection, a comparative account on properties of these fibers is presented. Among various types of fiber reinforcements, E-Glass, Low elastic modulus type carbon fiber (LM) and kevlar149 fiber are compared. According to the literatures reviewed,

- Glass fibers are denser than carbon or kevlar fibers.
- Tensile strength of all the fiber types presented is almost similar.
- Tensile modulus of LM carbon fiber is relatively higher, when compared to glass and kevlar fibers.
- Carbon fibre is very good conductor, while kevlar and glass are non-conductors.
- Kevlar is more fatigue resistant, while carbon and glass are somewhat but not totally sensitive to fatigue.
- Kevlar offers strong abrasion resistance, while carbon and glass fibers are less resistant.
- Carbon fiber is highly stable and is relatively non-sensitive to chemical degradation.

As per the comparative account, carbon fibers have salient properties than glass and kevlar fibers. This provides a reference for selection of carbon fibers as the main reinforcing material in FRPC's. Further research with nano-metric carbon reinforcements may open up the scientific window towards the development of advanced multifunctional composites for broader technological applications.

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