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Introduction to Glass Fiber-Based Composites and Structures

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1.1 Introduction

Composites are formed by the association of fillers, reinforcing fibers along with compactable matrix materials, and other components [1]. The origin of the matrix can be metallic, polymeric, or ceramic. This furnishes composites their surface appearance, form, resilience, and environmental tolerance. Most of the structural strain is borne by the fibrous reinforcement, giving macroscopic rigidity and strength [2]. Superior mechanical and physical properties can be given by a composite material because it incorporates the most desirable properties of its constituents while removing their least desirable properties [3, 4].

Glass Fiber-Reinforced Composite (GFRC) is a thermoset plastic resin that is reinforced with glass fibers [5]. Weight, dimensional stability, and heat resistance are given by fiber. Additives provide color, decide the surface finish, and influence many other characteristics, such as wear and flame retardancy. Complex chemical action requires manipulating glass fiber reinforced polymer (GFRP) composites [6]. Factors, including the form, quantity, and composition of the resins and orientation of reinforcements, determine the final properties [7]. Lightweight, high strength, corrosion endurance, dimensional steadiness, component consolidation and tooling minimizations, low moisture absorption, high dielectric strength, minimal finishing required, low moderate tooling cost, and design versatility are the benefits and characteristics of GFRC [8].

Rene Ferchault de Reaumur invented glass fiber. At the completion of the eighteenth century, large-scale glass fiber manufacturing began. It continued as a forgotten composite material until 1935, and it gained prominence only after fiberglass was turned into yarn. Fiberglass composite first finds its application in the aircraft industry. Since then, it has been expanded in various profit-making applications. Although glass has the best characteristics, it lacks reusability and bio-degradability. Therefore, researchers [9–12] are working at an approach that encourages both reusability and bio-degradability.

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Glass fibers are one of the most adaptable industrial and domestic materials in the current scenario [13]. They are readily available in abundance to meet their demand. Silica is the main ingredient of almost all glass fibers [14]. They demonstrate properties viz hardness, clearness, chemical resistance, constancy, and inertness, as well as fiber properties such as strength, flexibility, and stiffness, which are desirable. Glass fibers are used in the manufacturing of structural composites, printed circuit boards, and a wide variety of special-purpose items. One of the most prevalent fibers used in the reinforced polymer industry is fiberglass or glass fiber. Fiberglass is extremely flexible and can be converted into sheets.

For the manufacturing of fiberglass, it is melted and pushed in diameter through superfine holes [15]. The created glass threads can be knitted into thin sheets or condensed into bloated materials that can be utilized in soundproofing and isolation. GFRC is used in the manufacturing of a variety of products, such as cars, aircraft, pressure vessels, defense equipment, and consumer goods, etc. Fiberglass is more versatile than carbon fiber and less costly. It has the peculiarity of being sturdier as compared to numerous metals as well. These are lightweight and have good malleability [16]. For all the right reasons, GFRC has acquired the marketplace.

Earlier, the higher cost of polymers is found to be one of the reasons for its limited use in industrial application. However, the addition of fillers strengthened the GFRP properties and eventually decreased preparation and overall costs also. GFRC has a wide variety of applications in the aerospace, marine/shipping, construction, chemical, automobile, consumer commodities, and piping industries, etc. Laminated GFRC materials are used because of good corrosive resistance, better impact loading and damage tolerance, high specific strength, and rigidity. In Section 1.2, the application of GFRC is discussed in detail.

1.2 Applications

GFRCs are a favored material because of their enormous properties including electrical protection, strength, and toughness. Glass fiber fortified saps are utilized generally in the structure and development industry. They are utilized as a layer and/or cover for other underlying materials as well as a divider board; window outlines, reservoirs/containers, washroom utilities, lines, and channels are basic models. Boat frames, since the mid-1960s, have principally been made of GFRC. The utilization of GFRC in the consumer functionalities (reservoirs, pipelines, and pressure vessels) is genuinely standard. All three modes of transport, i.e. railways, roadways, and air transportation are another huge client of GFRC. As referenced earlier, fiberglass is quite possibly the most ordinarily utilized material in almost all engineering applications. Probably the most unmistakable uses of fiberglass are as follows:

1. The material utilized in the airplane and aeronautic trade must be steady and lightweight. S-glass possesses superior strength and modulus, making it a favored sort of fiberglass in the industrial sector. Also, S-glass likewise has better overlay solidarity to weight proportion, high weariness life, and good maintenance life at elevated temperatures.

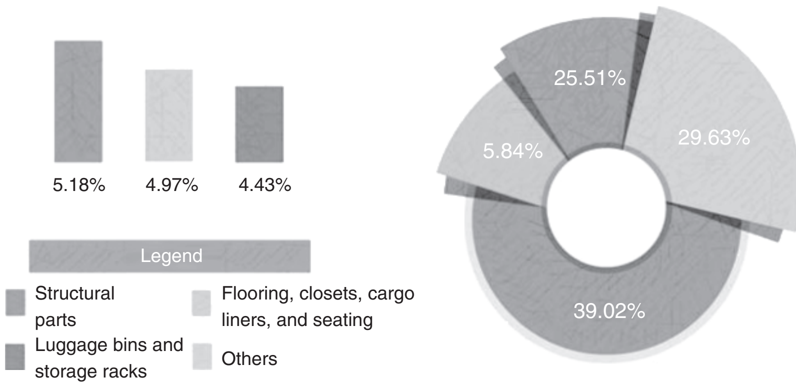


Figure 1.1 Global fiber-glass for aerospace industry market by application.

GFRC has been broadly utilized in avionics and aviation component as it better suits the applications [17]. Commonplace GFRC applications are structural parts, luggage bins and storage racks flooring, closets, cargo liners, and seating as shown in Figure 1.1. It is additionally broadly utilized in ground-dealing with hardware. It is commonly used to make protective layers in aero vehicles, flight deck shields, floorings, and armchairs of airplane. S-glass has more prominent mechanical properties as well as nonconductive. By offering lower radar warm profiles, it supports better stealth technology that gives these composites sharp edges for aviation equipment.

2. GFRC offers good dimensional constancy that makes it a perfect choice to be utilized in development. Decreased weight, low combustibility, sway obstruction, and high strength are altogether the properties that any development material ought to have, and GFRC is all that it requires to be. It is utilized in the development of both inside and outside parts of the business, private, and modern developments, going from washroom apparatuses to pool wall to lookout windows of mechanical structures to sun-based warming components.
3. GFRC is broadly used in various consumer commodities. These are utilized in the fabrication of furniture structures, decorative items, sports and gym equipment, etc. It is used as an essential material in consumer products because of its expanded flexibility, lower mass with superior strength, sturdiness, simple formability, great surface, and protection from corrosion and wear. It likewise discovers great purpose in the manufacture of home and furniture appliances viz rooftop sheets, bathroom accessories, racks, coffee tables, etc.
4. GFRC is also utilized for many applications where corrosion-resistant materials are required. For longer work-life in hostile and chemical process industries, GFRCs with proper additives are used for approximately 95% of corrosion-resistant equipment [18]. These materials possess good resistance to wear and corrosion. The above properties make it an ideal material for making equipment such as underground petrol tank, sewage systems, dam gates, drainage and chemical pipes, water and waste treatment areas, cooling towers, pollution

control equipment, tanks and vessels, pipe, ducting, hoods, fans, scrubbers, stacks, grating, and specialty fabrications.

5. Good electrical insulation property and stable mechanical behavior at elevated temperature make the GFRC an appropriate choice of material for its application in electrical appliances [14]. GFRCs have been extensively used in circuit board making, computer parts and accessories, transformers, mobile phones, switchgear, structural covers, and electrical components.
6. Good toughness and the better strength to weight ratio of GFRC give significant reason for its overwhelming acceptance in the marine and shipping industry. It has a better ability to be formed into different shapes with ease. These properties are undeniably fit for boat development. In spite of the fact that there were issues with water retention, the cutting-edge gums are stronger and they are utilized to simplify the sort of boats. Truth be told, GFRC is a lightweight material contrasted with different structural materials [19].
7. Low density with higher strength of GFRC has made it a favored development material choice in the automobile sector also. Various underlying components of a vehicle are made with fiberglass, like the strap in a belted-inclination tire. GFRC is likewise used to make rail line fishplates. It has assumed control over the automobile industry in abundance. It has supplanted traditional structure materials. It will keep on improving its quality with consistent enhancements and further turns of events. It has effectively fulfilled the necessities of the designing field partly, and it keeps on facilitating fulfill the prerequisites of different businesses. It has been widely utilized for car body-parts such as boards, seat, cover-plates, entryway boards, door, bumpers, engine cover, guards, and various vehicle accessories cover, etc.
8. Good wear resistance, low porosity, and nonstaining ability of GFRCs make them suitable for medical equipment applications. Because of their transparency, GFRCs are used for making X-ray beds.
9. Nowadays, GFRCs are commonly used in pressure application, as shown in Figure 1.2. With proper design consideration and analysis, it works safely for up to 1200 psi. For high temperature and military application also, it is applicable with the proper combination of reinforcement material and resins.

Figure 1.2 High-pressure containers prepared of thermosetting resin and glass fiber reinforcement. Source: Reproduced from Rajak et al. [3].

Composites are mostly suitable for the design of aircraft components such as wind turbine blades, pipelines, automobile structures, partitioning, seating, and marine construction. The character of composite is determined by the nature of reinforcement used, fiber orientation, method of molding, and operating conditions. In order to allow stress transfer, the mechanical behavior of a GFRC is essentially subjected to the mechanical characteristics of the fiber, chemical constancy, strength of the matrix, and the interfacial connection between the fiber and matrix. The shape of the component is provided by the matrix used. Reinforcements are man-made at the beginning, both by different physical techniques and by chemical synthesis. They are mass-produced and delivered to various factories for composite manufacturing because of the wide use of reinforcements. In course of production, glass fibers are utilized in various forms, such as long fibers, short fibers, and woven mats among various classes of artificial fibers. Glasses are easily available with lower cost and better properties making them a superior choice over other options. Centered on a particular application, glass fibers are of various kinds. Symbols like A-glass symbolizes alkali glass, C-glass embodies good chemical resistance, E-glass possesses properties suitable for an electrical application, S-glass is graded and nominated for structural purposes. In Section 1.3, classification of glass fiber is presented.

1.3 Classification of GFRC

Glass-fibers can be utilized in numerous varieties to suit explicit applications. Various types of glass-fiber have differing constituents that bring about a particular quality of each kind. The essential ingredient of different types of glass-fiber is the equivalent except for a couple of crude constituents. The amounts of all crude elements in each sort of glass-fiber are unique, subsequently providing each type with a novel arrangement of properties, as depicted in Figure 1.3. The fundamental crude elements that are utilized in the assembling of glass-fiber incorporate silica, soda ash, and limestone. Other constituents contain borax, magnesite, calcined alumina, feldspar, kaolin clay, etc. Silica sand contributes to glass formation and soda ash along with limestone brings down the melting point. Different fixings add to the enhancement of various properties. For instance, borax enhances the ability to resist chemical attack [5]. As discussed earlier, there are numerous sorts of fiberglass relying on the forming elements. The significant sorts of fiberglass, depicted in Figure 1.2, are as follows.

1.3.1 A-Type

Alkali glass (soda-lime glass), abbreviated as A-type glass is the most common variety of glass fiber available. About 90% of the overall glass production comprises alkali glass. It is one of the very widely used glass type that is used in making window panes, glass jars, bottles for beverages, and food items. Tempered alkali glass is utilized in the making of baking utensils. This type of glass is quite hard, extremely

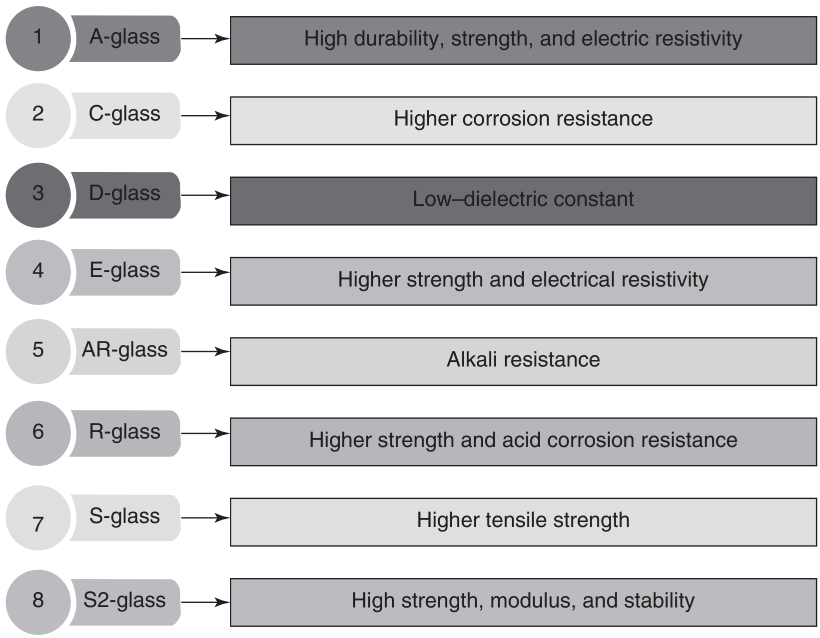


Figure 1.3 Categorization and related properties of different glass fiber composites.

workable, chemically stable, and relatively cheaper. It can be recycled *n* number of times. The main ingredients for the formation of A-glass consist of soda (Na_2CO_3), lime, silica (Si_2O_3), dolomite, alumina (Al_2O_3). Sodium chloride (NaCl) and sodium sulfate (Na_2SO_4) are considered to be the fining agents, which are also used in the production of soda-lime glass.

1.3.2 C-Type

Compound glass also termed as C-glass demonstrates the most superior safeguard from chemical attack. The occurrence of a large amount of calcium borosilicate provides structural stability against corrosive surroundings. This type of glass is utilized in the external coating of covers as surface tissue for lines and tanks, which hold water and synthetic compounds.

1.3.3 D-Type

The existence of boron-trioxide in D-glass gives it recognition for its low dielectric constant. This characteristic makes it suitable for its application in optical cables. D-glass fiber-reinforced composite possesses a very low coefficient of thermal expansion making it appropriate for electrical devices and cookware.

1.3.4 E-Type

This type of glass is an alkali glass normally termed electrical glass. It is a high-performance GFRP having lightweight used in marine, aerospace, and other industrial application. The constituent elements used in the production of E-type glass fiber composite are silica (SiO_2), calcium oxide (CaO), alumina (Al_2O_3), magnesium oxide (MgO), sodium oxide (Na_2O), boron trioxide (B_2O_3), and potassium oxide (K_2O). The significant characteristics that make E-glass a popular type of fiberglass are better strength, economical, higher stiffness, heat resistant, low density, fire-resistant, better endurance to chemicals, comparatively inert to wetness, better electrical isolation, and ability to uphold structural integrity in diverse circumstances.

1.3.5 R-, S-, and T-Type

These are trademarks for a similar kind of GFRP. They acquire prominent modulus and rigidity when contrasted with E-type GFRP. Their acidic strength and wetting properties are likewise better. These characteristics are attained by reducing the fiber filament radius. This variety of glass-fiber is created and aimed at aerospace and defense application.

1.3.6 S2-Type

This type of glass has more content of silica as related to other forms of glass fiber. Because of that, it has improved characteristics, superior weight performance, elevated compressive strength, high-thermal endurance, and advanced impact resistance. Most importantly, S2-type GFRPs are economical having 85% more tensile strength than conventional fiberglass. It has improved toughness and impact capabilities, together with better damage tolerance and composite durability.

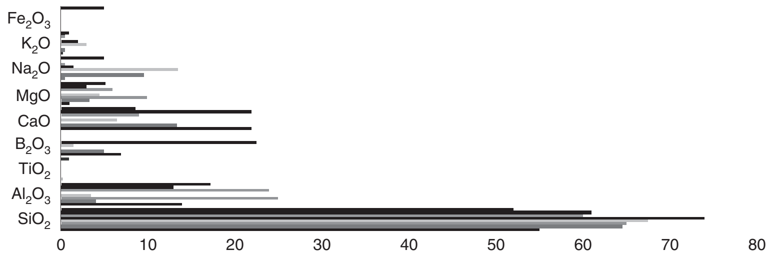
1.3.7 M-Type

This type of glass fiber possesses additional flexibility due to the presence of beryllium.

1.3.8 Z-Type

It is relatively transparent and utilized in several industries, involving the construction industry and 3D printing. This type of glass fiber is superior in mechanical strength, UV resistant, salt, alkali, acid, wear, temperature, and scratch resistance. It is perhaps the strongest as well as dependable kind of glass fiber.

For the above-described glass fibers, their constituent percentage is presented in Figure 1.4. Various mechanical as well as physical properties for example tensile



	SiO_2	Al_2O_3	TiO_2	B_2O_3	CaO	MgO	Na_2O	K_2O	Fe_2O_3
■ Basalt	52	17.2	1		8.6	5.2	5	1	5
■ EGR-glass	61	13			22	3		0.5	
■ R-glass	60	24			9	6	0.5	0.1	
■ D-glass	74			22.5			1.5	2	
■ A-glass	67.5	3.5		1.5	6.5	4.5	13.5	3	
■ S-glass	65	25				10			
■ C-glass	64.6	4.1		5	13.4	3.3	9.6	0.5	
■ E-glass	55	14	0.2	7	22	1	0.5	0.3	

Figure 1.4 Constituent percentage for different type of glass fiber.

Table 1.1 Physical and mechanical properties of glass fiber.

Fiber	**Density ($g\,cm^{-3}$)**	**Tensile strength (GPa)**	**Young's modulus (GPa)**	**Elongation (%)**	**Coefficient of thermal expansion (10^{-7}/°C)**	**Poisson'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
S2-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
D-glass	2.11–2.14	2.415	51.7	4.6	25		1.465
R-glass	2.54	4.135	85.5	4.8	33		1.546
ECR-glass	2.72	3.445	80.3	4.8	59		1.579
AR glass	2.70	3.241	73.1	4.4	65		1.562

Source: Sathishkumar et al. [8].

strength, Young's modulus of elasticity, coefficient of thermal expansion, refractive index, density, and Poisson's ratio of glass fibers are given in Table 1.1.

1.4 Classifications Based on Form

Glass fibers are primarily considered as reinforcement for polyester, phenolic resins, and epoxy. They are economical as well as available in a variety of arrangements. The assembly of distinctive fibers is termed as a continuous strand. The collection of similar strands comprises the roving form. A length of about 5–50 mm strands encompasses chopped fibers. Woven fabric, nonwoven mats, chopped strand mats,

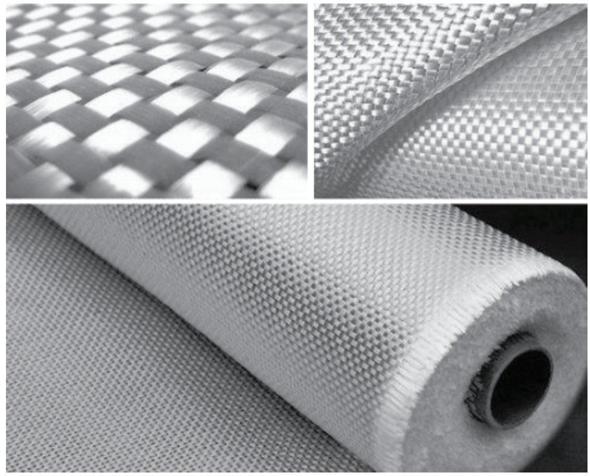


Figure 1.5 600 grams per square meter (GSM) fiberglass woven roving mat. Source: Modified from Anon [21].

veil mats, and tow are some of the available forms of fiberglass [20]. Maximum properties are achieved when glass fiber is in form of tow or roving. In this type, fiberglass is delivered in the form of reels, which can be unrolled and cut as necessary or taken into filament winders. The fibers of fiberglass must remain under tension to maintain their mechanical properties. A randomly looped continuous strand of fiber in a thin pile arrangement forms the veil mats. They are not suitable for structural applications. The woven fabrics are relatively stronger, shown in Figure 1.5, as they are sewed together and are bundled into yarn [22]. Fibers of length of 3–4 in. are randomly arranged in chopped strand mats [23]. This type of glass fiber is cheaper and hence the most commonly used glass fiber as well. However, the length of fiber is shorter, making it less strong as compared to others.

1.5 Structure

Silica-based-inorganic glasses are amorphous and hence identical to organic glass polymers. They are devoid of any crystalline material-characteristic long-range order. At 1800 °C, pure, crystalline silica melts. However, with the addition of certain metal oxides, the bonding of silicon oxide can be broken down. This can cause the lowering of glass transition temperature and hence the formation of a series of amorphous glasses.

In Figure 1.6, 2D arrangement of silica is presented. Silicon is covalently bonded with an oxygen atom in each polyhedron. Figure 1.6b shows the modification in structure when Na_2O is added. Sodium ions are connected to the atoms of oxygen; however, they are not specifically joining the network. The addition of other kinds of metal oxide helps to modify the structure of the network and the bonding and, subsequently, the properties. Remember that this contributes to the isotropic properties in the three-dimensional network structure of glass. Young's modulus of elasticity and coefficient of thermal expansion of the glass fiber remain uniform along the longitudinal and transverse axis.

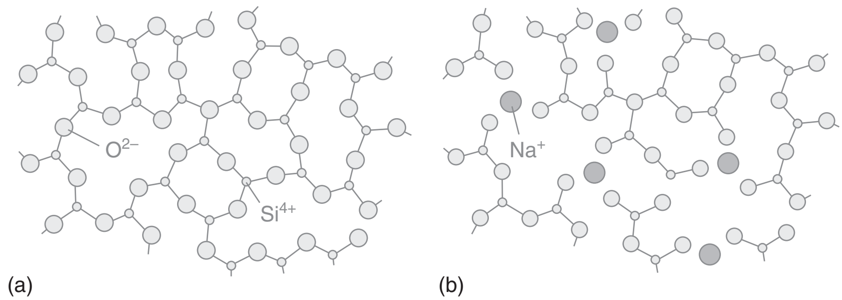


Figure 1.6 Amorphous glass structure: (a) a 2D illustration of silica glass arrangement and (b) a reformed arrangement with Na_2O added to (a). Source: Chawla [24].

1.6 Mechanical Properties

Singh et al. [25] studied mechanical and tribological characteristics of 20 wt% short glass fiber reinforced with 80 wt% poly-oxy-methylene (POM) and 20 wt% poly-tetra-fluoro-ethylene (PTFE) blend. Sixty-three percent (i.e. from 46.5 to 75.36 N mm^{-2}) increase in tensile strength of the POM/PTFE blend reinforced with 20 wt% short glass fiber was reported. Vijay and Srikantappa [26] from their experimental study found superior mechanical and wear behavior of MoS_2 filled glass-epoxy composites as compared to unfilled composite. Mechanical properties of different forms of glass fiber with resins and volume fraction are listed in Table 1.2. Shanti and Satyadevi [47] developed a glass fiber reinforced (GFR) composite with graphite as a filler and showed that these types of composites exhibit more mechanical and thermomechanical strengths compared to the composite without a filler. Kunishima et al. [48] investigated the tribological behavior of GFRP-polyamide 66 composite in contact with carbon steel under high contact pressure, sliding, and grease-lubricated conditions. They found sliding causes peeling off of the fibers and scratches on polyamide also [49]. Although a multitude of glass fiber forms exists, the most important types, resins, curing agent, testing standards their mechanical strength properties are listed in Table 1.2. Rajamahendran et al. [19] experimentally analyzed the mechanical and tribological behavior including sliding wear E-glass fiber-reinforced interpenetrating polymer networks (IPN) composites using a pin-on-disk apparatus. They found a massive increase in wear resistance with the addition of 5% alumina filler into the matrix material. Ravi et al. [50] experimentally investigated using a pin-on-disk wear tester to study the sliding wear behavior of the friction stir welded polyamide 66 including and excluding the glass fiber reinforcement.

Vijaya Kumar et al. [51] numerically and experimentally studied about the mechanical properties of bamboo–GFR hybrid composite by changing the lamina orders. They opined that the lamina with order G/B/G/G (45% E-glass fiber, 15% bamboo fiber, and 40% epoxy resin) composite specimen offers more mechanical strength as compared to other lamina orders.

Table 1.2 Mechanical properties of GFRCs available in literature.

Type of glass fiber	Resin	V_f	Testing standard	Tensile strength (MPa)	Tensile modulus (MPa)	Elongation at break (%)	Flexural strength (MPa)	Impact strength	Interlaminar shear strength (MPa)	References
Woven mat	Polyester	0.25	ASTM D412 (T)	1.601	80.5	20.0	—	41.850 (J)	44.7	[27]
Woven mat	Polyester with 3% oligomeric siloxane	0.37	ASTM D-3039 (T), ASTM D 790 (F), ASTM D 2344 (S)	395.8	18 000	3.9	399.4	—		[28]
Woven mat	Polyester	0.33	ASTM D 638-97 (T), 2810 E6 (T)	249	6 240	—	—	—	—	[29]
Woven mat	Polyester	—		189.0	—	—	—	—	—	[17]
Chopped strand	Polyamide66 (PA66)/poly-phenylene sulfide (PPS) blend	0.30	GB/T 16,421-1996 (T) GB/T 16,419-1996 (F), GB/T 16,420-1996 (I)	—	124	—	159	98.2 (kJ m^{-2})	—	[30]
Woven mat (0°/90°)	Poly-phenylene sulphide (PPS) blend	0.42	PS25C-0118 (T)	200	—	—	—	10 (J)	—	[31]
Woven mat (non-symmetric)	Polyester	—	362F (BS, 1997) (T)	220	7 000	0.055	—	—	27	[32]
Woven	Polyurethanes	0.49	ASTM D3039 (T), ASTM D790M (F), ASTM D2344 (S)	278	18 654	—	444	—	—	[33]
Chopped strand mat	Polyester	0.60	ASTM D638 (T)	250	325	0.022	—	—	30	[34]
Woven mat	Polyester (acid resistant resin)	—	ASTM D 2344 (S)	—	—	—	—	—	—	[35]

(*continued*)

Table 1.2 (Continued)

Type of glass fiber	Resin	V_f	Testing standard	Tensile strength (MPa)	Tensile modulus (MPa)	Elongation at break (%)	Flexural strength (MPa)	Impact strength	Interlaminar shear strength (MPa)	References
Chopped strand mat	Polyester ruin	0.015	ASTM E 399 (T)	—	3 000	—	16.5	—	—	[36]
Chopped strand + vertical roving	Polyester	—	ASTM D 3039 (T), ASTM D 5379 (I)	103.4719	—	—	—	37.926 (J)	—	[37]
Virgin fiber	Polyester	—	ASTM D256 (T), ASTM D2240 (I)	64.4	7 200	1.8	—	645.1 ($J\,m^{-1}$)	—	[38]
Glass	Polyester (3 wt% Na-MMT)	0.40	ASTM-D638 (T), ASTM-D790 F, ASTM-D256 (I)	130.03	—	—	206.15	153.50 ($kJ\,m^{-2}$)	—	[39]
Chopped strand	Epoxy (5.1 Vf fly ash)	3.98	ASTM standard	—	—	—	—	0.0176 $J\,mm^{-2}$	18.2	[40]
Woven (biaxial stitch)	Epoxy	0.57	ASTM D 2355 (S)	—	—	—	—	—	—	[41]
Randomly oriented	Epoxy (10 wt% SiC)	0.5	ASTM D 3039-76 (T), ASTM D 256 (I)	179.4	6 700	—	297.82	1.840 (J)	18.99	[42]
Woven	Epoxy (0.5 wt% MWCNTs)	0.73	ASTM D 2344 (S)	—	—	—	—	—	41.46	[43]
Unidirectional	Epoxy	0.55	ASTM D 3039 (T)	784.98	—	0.032	—	—	—	[44]
Woven	Epoxy (6 wt% joc)	0.60	ASTM D 3039 (T)	311	18 610	3.8	—	—	—	[45]
Woven + (35 wt% short borosilicate)	Epoxy	—	—	355	43 700	1.65	—	—	—	[46]

T, tensile test; F, flexural test; I, impact test; S, shear test; joc, Jatropha oil cake; Na-MMT, sodium montmorillonite; MWCNT, multiwalled carbon nanotube.
Source: Modified from Sathishkumar et al. [8].

1.7 Conclusion

The demand for lighter, stronger, and economical glass-fiber-based composite materials requires constant and incremental research. In order to bring in as best possible details of GFR composites, types based on composition, different forms, and orientations are presented. Their use in industrial, domestic, aerospace, construction, and chemical corrosive environment is also discussed. Proper selection of glass fiber, reinforcement, and resins are critical as they are the key element to produce Glass Fibers-Based Composites at around 70–75% by weight and approximately 50–60% in size. The necessity to improve the quality of GFR composites with a different combination of fillers and chemical compositions is an intriguing area of research. Advances in glass fiber formulation acknowledge for strengths in parity with carbon fibers and equivalently significant for mass manufacturing by the efficient process. It is expected that this chapter will provide the fundamental knowledge about GFR composites to educationists and investigators willing to work in this area.

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