INTRODUCTION

A composite material is a material consisting of two or more distinct parts. By this broad definition, nearly all materials occurring in nature can be classified as a composite material. Even atoms can be considered a composite being composed of electrons, protons, and neutrons. A narrower definition of a composite material is one where two or more chemically distinct and mechanically separable materials, on the macroscale, having a distinct interface separating them, are combined to give desirable overall properties. For example, concrete and steel are combined to form reinforced concrete taking advantage of the high compressive strength of concrete and the high tensile strength of steel. In the case of advanced composite materials, the matrix or fiber materials alone have a limited structural value. The matrix of a composite serves to bind reinforcement together to form a composite structure and protect reinforcement from physical damage and chemical attack, while the fibers provide strength and stiffness. Therefore, the combination of fiber and matrix materials provides a synergistic effect on the overall mechanical properties.

In civil infrastructure, the increasing use of composite materials has paralleled technological development and advances in materials. Advanced systems and components such as suspension bridges, aircraft, and even microcomputers are dependent on available materials with characteristics to withstand service conditions and prevent failure. Irrespective of the industry or application,
the final limitation on advancement depends on availability of materials. Composites can address this limitation with their tailorble characteristics and properties to satisfy design criteria of any complex engineered systems.

The existence of composite materials is arguably as old as life itself, with examples occurring in nature, such as wood and bone. Man-made composites can be traced back in time to approximately 4000 BC, where biblical references in the Book of Exodus state “do not give them straw for their bricks, make them find their own straw,” indicating that straw was mixed with clay to manufacture straw-reinforced bricks. This practice was so successful in ancient Egypt that it is still in use in many parts of the world today. Later, ancient Romans invented concrete and built many structures and monuments with it, including the Pantheon in Rome, which was constructed more than 2000 years ago and stands to this day. Contemporary examples of man-made composites include reinforced concrete and advanced composites such as those discussed in this handbook.

CHARACTERISTICS OF COMPOSITE MATERIALS

A composite material consists of one or more discontinuous phases (reinforcement) embedded in a continuous phase (matrix) with an interface between them; that is, a composite consists of reinforcement in a matrix with the interface acting as the bond between them. Table 3.1 lists the description of each of the three composite constituents.

The performance specific design of composite materials suggests that a wide range of factors influence the properties of a composite. The following list provides a summary of possible factors that can alter composite properties and influence performance:

- Properties of composite constituent materials
- Distribution of constituent materials
- Interaction (bonding) among constituents
- Geometry of the reinforcement, specifically its shape, size, and size distribution
- Reinforcement concentration or volume
- Homogeneity or uniformity of the composite system
- Orientation of constituents

MATRIX CONSTITUENTS

The matrix of a composite material serves to bind the reinforcement together, transfers loads to the reinforcement, and acts as a barrier to minimize damage from environmental attack or during handling. The matrix material also has the largest influence on the shear, transverse, and compressive

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**TABLE 3.1**

<table>
<thead>
<tr>
<th>Composite Constituent</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reinforcement</td>
<td>This is the discontinuous phase, which is strong and/or stiff and typically lightweight</td>
</tr>
<tr>
<td>Matrix</td>
<td>This is the continuous phase that transfers the load among reinforcement, provides protection to reinforcement, and is typically lightweight</td>
</tr>
<tr>
<td>Interface</td>
<td>This provides bond between reinforcement and matrix and can be strong or weak, depending on application</td>
</tr>
</tbody>
</table>
strength of the composite. Matrices are typically polymers (thermosets or thermoplastics), metals, or ceramics. The selection of matrix material is often influenced by the required temperature performance of the composite; polymers are usually selected for lower temperatures and ceramics are used in high-temperature applications. Figure 3.1 shows temperature ranges associated with typical matrix materials.

Metal and ceramic matrices have not been used in civil infrastructure applications because of cost. Polymers are the most commonly used form of matrix in civil infrastructure applications. Advantages of polymer matrices include their low cost, ease of processing, low density, and good chemical resistance. Disadvantages associated with the polymer matrix include low strength and stiffness, low operating temperature, deterioration due to ultraviolet radiation exposure, and degradation of mechanical properties due to moisture absorption.

Polymer matrices are classified into thermosets and thermoplastics, based on the way they respond to heat. When heated, thermosets undergo permanent reactions, while thermoplastics only undergo temporary physical change. Thermosets are formed by irreversible chemical reactions between polymer chains (cross-linking), while thermoplastics are composed of long polymer chains that can be heated, deformed, and cooled, with no chemical reaction occurring. A detailed discussion of these two general classes of polymers follows in the ensuing sections.

**THERMOSETS**

Thermosets are cross-linked polymers that have undergone an irreversible chemical reaction to permanently connect all molecular chains with covalent bonds. This material sets (or cures) into shape by adding a catalyst (or by heating). The processing of a thermoset involves an exothermic reaction where the catalyst (or curing agent) is mixed with a polymer resin—both are generally liquid. The resulting mixture is liquid and it begins to set (or gel). As the polymer gels, it undergoes an irreversible chemical reaction to form a 3-D network of cross-links, gaining a higher degree of rigidity. During the cooling period, which follows the exothermic reaction, residual and shrinkage stresses can occur. The properties of the matrix are dependent upon the degree of cross-linking and their density. It is important to note that the rigid, 3-D molecular structure will not regain processability under any circumstances; it has transformed permanently.

Typical thermosets include epoxy, polyester, and phenolic resins. This class of polymers is the most widely used in civil infrastructure applications because they outperform thermoplastics in terms of mechanical properties, chemical resistance, thermal stability, and overall durability. Also, thermoset matrices have a stronger interface bond between polymeric chains. The disadvantages include long cure times, not recyclable, and brittle behavior.

Temperature plays an important role in the properties of all polymer materials. In the case of thermosets, exposure to elevated temperatures (close to but below the glass transition temperature, \( T_g \)) greatly influences the mechanical properties and durability of the matrix. The glass transition temperature, \( T_g \), is the temperature at which a material transitions from a hard and brittle state into a soft and rubberlike state. Therefore, when the exposure temperature reaches \( T_g \) of the matrix, a dramatic reduction in stiffness is observed as illustrated in Figure 3.2.

The mechanical properties of thermosets are not only temperature dependent but also time dependent. This makes the material viscoelastic, with stress–strain behavior, as shown in Figure 3.3. This viscoelastic behavior makes polymer matrices susceptible to creep effects.
Thermoplastics

Thermoplastics are linear or branched polymers, with molecular chains that are connected or formed by weak intermolecular bonds (van der Waals bonds). Unlike thermosets, thermoplastics do not cure or set when heated; in fact, they soften and become more fluid as the temperature increases. The processing of thermoplastics therefore involves softening/melting by applying heat; as the material cools, it hardens into the shape of the mold containing it. There is no chemical reaction or cross-linking as with thermosets; the material changes are entirely physical. Because the changes are reversible, thermoplastics can be recycled and reprocessed, although after many recycling iterations, the polymer tends to degrade.

The properties of thermoplastics are strongly dependent on crystallinity, temperature, and time. Like thermosets, the stress–strain behavior of thermoplastics is viscoelastic, as shown in Figure 3.4. In general, thermoplastics are more ductile than thermosets, as presented in Figure 3.4. Thermoplastics can display failure strains much greater than 100%, whereas the failure strains of thermosets are typically less than 10%. As displayed in Figure 3.4, the strength of a thermoplastic is dependent on strain rate and temperature.

Typical thermoplastics include polyethylene, polycarbonate, nylon, polyether–ether ketone resins. This class of polymers is rarely used in civil infrastructure applications because of their poor chemical resistance, unknown processing for composites properties, high shrinkage (as much as 20%), and
poor durability (i.e., moisture plasticizes or softens the polymer chains). Also a comparison of the properties of a thermoset (epoxy) and a thermoplastic (polycarbonate) shows that thermoplastics have much lower stiffness and strength than thermosets (see Table 3.2). The advantages of a thermoplastic, as compared to thermosets, include short melting times, easy processing (no catalysts needed during processing), recyclable, and good fracture toughness (ductility).

Thermoplastics can be amorphous and semicrystalline. The stiffness of thermoplastics also depends on temperature, with significant decreases in stiffness observed with exposure to temperatures at or greater than the glass transition temperature, \( T_g \). This dependence however is most pronounced for amorphous than semicrystalline thermoplastics as exhibited in Figures 3.5 and 3.6.

![FIGURE 3.4 Load-rate- and temperature-dependent stress–strain behavior of thermoplastic matrices.](image)

**TABLE 3.2**

Typical Properties of Thermoset and Thermoplastic Polymers

<table>
<thead>
<tr>
<th>Property</th>
<th>Epoxy</th>
<th>Polycarbonate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, ( \rho ) (g/cm(^3))</td>
<td>1.2–1.3</td>
<td>1.0–1.2</td>
</tr>
<tr>
<td>Modulus of elasticity, ( E ) (GPa)</td>
<td>3–4</td>
<td>2.2–2.4</td>
</tr>
<tr>
<td>Ultimate strength, ( \sigma_{\text{ult}} ) (MPa)</td>
<td>55–130</td>
<td>45–70</td>
</tr>
<tr>
<td>Thermal expansion, ( \alpha ) (10(^{-6})/°C)</td>
<td>45–65</td>
<td>70</td>
</tr>
<tr>
<td>Failure strain, ( \varepsilon_f )</td>
<td>1–8</td>
<td>50–100</td>
</tr>
</tbody>
</table>

![FIGURE 3.5 Logarithm of stiffness versus temperature for an amorphous thermoplastic matrix.](image)
That is, the loss of stiffness at the glass transition temperature is not as severe in a semicrystalline thermoplastic, which displays a distinct melting temperature, \( T_m \). There is no noticeable \( T_m \) for amorphous thermoplastics (see Figure 3.5).

**REINFORCEMENT CONSTITUENTS**

As previously mentioned, improved properties over parent constituent materials are the most desirable characteristic of composites, for example, strength, stiffness, and toughness. These properties are actually highly dependent on the type and geometry of the reinforcement. Composites are generally classified based on reinforcement geometry into fiber-reinforced composites or particulate-reinforced composites. Fiber-reinforced, or fibrous, composites have their properties derived primarily from the reinforcement. As with the reinforcement, fibrous composites are typically strong, stiff, and tough and can perform well at elevated temperatures. Particulate composite properties, on the other hand, are primarily derived from the matrix. In this section, we discuss a number of reinforcement materials, with particular emphases on those used in civil infrastructure composite applications.

Most of the materials used as reinforcement for composite materials consist of elements found in the first two rows of the periodic table. The elements include beryllium (Be), boron (B), carbon (C), magnesium (Mg), aluminum (Al), and silicon (Si). These elements are considered strong, stiff, and light; they form covalent bonds and are brittle, which makes them sensitive to flaws. The specific reinforcement and chemical composition include

- Glass (silica, \( \text{SiO}_2 \); calcium oxide, \( \text{CaO} \); etc.)
- Carbon (graphite, C)
- Kevlar\textsuperscript{®}, Spectra\textsuperscript{®} (organic, carbon based)
- Silicon carbide (SiC)
- Aluminum (\( \text{Al}_2\text{O}_3 \))
- Boron (B)
- Beryllium (Be), which is highly toxic

The three most popular reinforcing materials are glass, carbon, and silicon carbide—in that order—which directly correlate with cost. Glass and carbon are the most widely used reinforcement materials for civil infrastructure composite applications because of cost. For applications that require large amounts of materials, glass is the most popular because it is the least expensive; for example, most FRP structural sections fabricated by pultrusion are reinforced with fiberglass. However, there are a number of applications where carbon is more cost effective because of its superior strength.
and stiffness as compared to glass. These applications include seismic retrofit of concrete columns using carbon fiber wrapping to enhance concrete confinement, where light weight and high strength is required.

**Fibrous Reinforcement**

Fibrous reinforcement includes continuous fibers, discontinuous fibers, whiskers, and carbon nanotubes (CNTs). The most common types of fibrous reinforcement are glass, carbon, and aramid fibers—other types of fibers include boron, silicon carbide (SiC), alumina, and sapphire, all of which are used in special applications. The choice of fiber for a specific application depends on the desired mechanical and environmental properties, but the most important deciding factor is typically cost. Also, there is a number of compatibility issues that must be taken into account when combining these various types of reinforcement with matrix materials; the typical matrix selected for different fibers is shown in Table 3.3.

Continuous fibers are available in long continuous fiber bundles, also known as yarns, tows, strands, and rovings, with individual fibers having a length-to-diameter ratio that approaches infinity and a diameter on the order of 10 μm (Astrom, 1997). For reinforcement, fibers are used in bundles, configured as unidirectional, woven, or braided fabrics; these configurations also affect the properties of the composite, with unidirectional being the most desirable based on strength and stiffness, while the other two being more desirable from fabrication and handling perspectives.

One advantage of using continuous fiber reinforcement is the reduction in the number of flaws and flaw sizes in the material, both of which help the composite approach its theoretical strength. On average, the theoretical longitudinal strength of a fiber is approximately $\sigma_{th} \approx E/2\pi \approx E/6.3$, whereas the typical measured strength of a fiber is approximately $\sigma_{me} \approx E/15$, where $E$ is a fiber’s longitudinal modulus of elasticity (Felbeck and Atkins, 1984). There are some material geometries that approach the theoretical strength, for example, iron whiskers with a theoretical strength of $\sigma_{th} \approx 200$ GPa/6.3 = 31.7 GPa and measured strength of $\sigma_{me} \approx 14$ GPa. Note that measured strength is approximately half of the theoretical strength in this case (Felbeck and Atkins, 1984). Another example is multiwall CNTs, which contain walls with about 15 graphene layers (a single layer of carbon atoms in hexagonal arrangement) forming a cylinder of 10–15 nm outside diameter, 2–4 nm inside diameter, and about 10–20 μm long, capable of reaching a strength of 150 GPa and elastic modulus of 800–900 GPa because of the defect-free structure.

An examination of fibers at the crystal level is useful when examining the results of theoretical strength values. In an unstressed condition, the repulsive and attractive forces between atoms in a crystal are in equilibrium for a given spacing of atoms. If a crystal is strained, however, the net force resisting the external pulling force increases from zero as the atoms move away from equilibrium positions. Eventually, a maximum force is reached and the force between atoms decreases as the spacing between atoms increases. The ideal strength of the material in terms of cohesion is related to that maximum value. **Figure 3.7** depicts a typical curve for applied force or stress versus distance at the atomic level—the springs represent the bond between two atoms.

### Table 3.3

<table>
<thead>
<tr>
<th>Matrix</th>
<th>Fiber Choice</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polymer</td>
<td>Glass, carbon, aramid (Kevlar, etc.)</td>
</tr>
<tr>
<td>Metal</td>
<td>Silicon carbide, boron, alumina (large diameter)</td>
</tr>
<tr>
<td>Ceramic</td>
<td>Silicon carbide, alumina, and sapphire</td>
</tr>
</tbody>
</table>
Since the force or stress, $\sigma$, is periodic, the relationship between stress and displacement can be expressed as follows:

$$\sigma = \sigma_{\text{max}} \sin \left( \frac{2\pi x}{\lambda} \right)$$

(3.1)

where

- $\lambda$ is an artificial wavelength
- $x$ is the displacement relative to the interatomic equilibrium spacing, $a_o$, during a unidirectional tensile loading condition

For small displacements, $x$, the crystal strain is defined as $d\varepsilon = dx/a_o$. In the elastic region around the origin, from Hooke’s law, $d\sigma/d\varepsilon = E$. Substituting the strain definition into Hooke’s law yields the following:

$$\frac{d\sigma}{dx} = \frac{E}{a_o}$$

(3.2)

From Equation 3.1,

$$\frac{d\sigma}{dx} = \frac{2\pi}{\lambda} \sigma_{\text{max}} \cos \left( \frac{2\pi x}{\lambda} \right)$$

Since $2\pi x/\lambda \ll 1.0$, $\cos(2\pi x/\lambda) \approx 1.0$. Therefore, for small values of $x/\lambda$, combining Equations 3.1 and 3.2 results in a maximum theoretical fiber strength of

$$\sigma_{\text{max}} = \frac{\lambda E}{2\pi a_o}$$

If it is assumed that $\lambda$ and $a_o$ are approximately the same size (i.e., $\lambda \approx a_o$), then

$$\sigma_{\text{max}} \approx \frac{E}{2\pi}$$

The discrepancies between theoretical and measured tensile strength of brittle fibers can be attributed to the presence of microcracks or flaws within the fiber. Statistically, a flaw of a given size is less likely to occur in a small lump of material as opposed to a larger quantity of the same material. For instance, the size effect is evidenced by lower measured tensile strengths of thick rods versus thin fibers. Flaws in the fiber act as stress concentrations that raise local stresses around the flaws to the theoretical maximum although stresses remain relatively low away from flaw locations.
Bonds adjacent to a flaw or crack tip can be broken, and crack opening occurs as illustrated in Figure 3.8. All missing bonds due to crack opening are redirected to the two atoms adjacent to point B at the crack tip giving rise to a stress concentration, as shown in Figure 3.8.

Fiber reinforcement does not follow a classification system based on physical properties (like matrices); rather, fibers are classified based on their material composition. As indicated earlier, there are a number of materials that have been used to produce fibers. A detailed discussion of the most important fiber materials ensues in the following sections.

Glass Fibers
Glass fibers are typically used in low-cost applications of polymer matrix composites. The primary advantages of glass fibers are their low cost and high strength, along with typical glass properties such as hardness, corrosion resistance, and chemical inertness. However, glass fibers also possess some disadvantages, including

- Low modulus of elasticity, typical of all glass fibers.
- Poor abrasion resistance, where rubbing of fibers together results in surface flaws, thus lowering strength. Consequently, glass fibers are manufactured with various protective coatings.
- Poor adhesion to polymer matrix resins, especially in the presence of moisture. The poor adhesion requires the use of chemical coupling agents such as silane.

There are different types of glass fiber available for various applications, including “A” or “AR” glass for alkaline resistant, “C” glass for corrosion resistance, “E” glass with enhanced electrical properties, “S” and “R” glass for high strength and stiffness, and some other specialized compositions. E-glass offers high tensile strength and excellent durability characteristics, which is the reason it serves as a general purpose grade of glass fiber and is the most widely used type of glass (Astrom, 1997). S- and R-glass display higher strength, stiffness, and temperature tolerance when compared to E-glass; however, the cost of S- and R-glass can be three to four times that of E-glass. Table 3.4 provides an overview of the properties of various glass-fiber types. All glass fibers are composed of an amorphous silicon oxide, SiO₂ (or silica), as the main constituent molecule. Other constituent molecules include those listed in Table 3.5. These constituent oxides typically have a 3-D isotropic structure (unlike carbon and organic fibers, which are discussed later) that gives glass its strength and stiffness.

Structure of glass is based on a silicon dioxide, SiO₂, backbone in the form of (SiO₄)₄ tetrahedral because SiO₂ molecules analogous to carbon dioxide molecules do not exist. Instead, in nature, SiO₂ is often found as a crystalline solid with the structure shown in Figure 3.9.
Every silicon atom is bonded to four oxygen atoms tetrahedrally; thus, every oxygen atom is bonded to two silicon atoms. SiO\(_2\) in this crystalline form is called silica, which is often identified as quartz (large crystals) or sand (miniscule crystals). In order to manufacture glass, silica particles are heated until melting and then cooled down quickly. During the melting process, the silica and oxygen atoms break out of their crystal structure. If the cooling process is slow, the atoms slowly line up back into their crystalline arrangement, whereas in a quick cool down, silica atoms are stopped in their current position and are unable to return to the crystalline arrangement. For structural application,

| TABLE 3.4 | Typical Properties of Glass Fibers |
|---|---|---|---|---|---|---|---|
| Properties | E-Glass | A-Glass | S-Glass | C-Glass | R-Glass | D-Glass | High Modulus |
| Density, \( \rho \) (g/cm\(^3\)) | 2.54 | 2.45 | 2.49 | 2.45 | 2.58 | 2.14 | 2.89 |
| Tensile strength, \( \sigma_{ult} \) (GPa)\(^a\) | 3.45 | 3.30 | 4.58 | 3.31 | 4.40 | 2.50 | 3.40 |
| Elastic modulus, \( E \) (GPa) | 72.4 | 69.0 | 85.5 | 69.0 | 84.8 | 55.0 | 110.4 |
| Diameter, \( d \) (\(\mu\)m) | 3–20 | — | 8–13 | — | — | — | — |
| Thermal expansion, \( \alpha \) (10\(^{-6}\)/°C) | 5.0 | — | 2.9 | 6.3 | — | 3.1 | — |
| Max operation temp. (°C) | 550 | — | 650 | 600 | — | 477 | — |


\(^a\) Virgin strength values of fresh-drawn fibers (measured by ASTM D3379) can yield up to 3.5 GPa for E-glass and 4.8 GPa for S-glass, but actual values are only 1.74 GPa for E-glass and 2.1 GPa for S-glass (which constitutes about 50% reduction) because of damage produced during the various stages of processing.

| TABLE 3.5 | Typical Composition of Different Types of Glass Fibers |
|---|---|---|---|---|
| Material | A-Glass | C-Glass | E-Glass | S-Glass |
| Silicon oxide (SiO\(_2\)) | 64 | 65 | 54 | 64 |
| Aluminum oxide (Al\(_2\)O\(_3\)) | 1 | 4 | 15 | 25 |
| Zirconium oxide (ZrO\(_2\)) | 13 | — | — | — |
| Calcium oxide (CaO) | 5 | 14 | 17 | — |
| Magnesium oxide (MgO) | — | 3 | 5 | 10 |
| Sodium oxide (Na\(_2\)O) | 14 | 8 | 0.6 | 0.3 |
| Boron oxide (B\(_2\)O\(_3\)) | — | 5 | 8 | — |
| Titanium oxide (TiO\(_2\)) | 3 | — | — | 0.2 |

most glass fibers are manufactured by melting sand and adding sodium carbonate. The sodium ions are ioni
cally linked to the oxygen atoms but are not part of the network, as shown in Figure 3.10.

Glass can be tailored to various applications with the addition of oxides to the basic composition, as shown in Table 3.4. The typical materials used to produce glass are sand, limestone, and alumina. These materials are melted in a refractory furnace at 1260°C, and at this stage the glass is also refined. The melted glass then passes through platinum bushings so as to form the fibers. Next, the fiber surface is chemically treated with a protective coating and a chemical coupling agent, called size, to promote adhesion to the matrix material. The chemically treated glass fibers are then wound onto a spool at a high speed or, in some cases, chopped for further processing.

The chemical treatment is necessary to reduce damage sustained when fibers rub against one another during processing. The protective coating or size, in addition to helping minimize fiber damage, also improves adhesion between fiber and matrix. Two general types of sizes are available for glass fibers: starch–oil sizes that are temporary and compatibility sizes that serve as coupling agents. A temporary size acts as a lubricant to prevent abrasive wear during processing and imparts antistatic properties and must be removed prior to bonding with matrix materials. A compatibility size acts as a coupling agent and protects the glass fiber from moisture effects. Organo-functional silanes, X₃Si(CH₂)ₙY, are commonly used as compatibility sizes that are chemically linked between the glass surface and the matrix. As shown in Figure 3.11, the organo-functional group, Y, is intended to react with a polymer matrix to form strong covalent bonds and may also form physical bonds or van der Waals bonds. The hydrolysable group, X, is essential for generating intermediate silanols to establish hydrogen bonds with the glass-fiber surface. Basically, X bonds to the glass fiber, while Y bonds to the matrix (Agarwal and Broutman, 1990).

Glass-Fiber Terminology
Composite glass-fiber reinforcement is available in bundles of individual fibers or filaments called strands or ends, which consists of 204 filaments. The strands are further bundled into groups
called rovings, which are wound onto a spool for packaging. These rovings are then stitched together to form a band used in composite fabrication. Rovings can also be used directly in composite fabrication, particularly pultrusion, filament winding, and other manufacturing techniques, which are discussed in Chapter 2. For some manufacturing techniques, it is more practical to use glass fibers in forms other than bands and rovings, including chopped strands, chopped strand mat, and woven fabric or cloth, woven fabric being one of the most commonly used forms.

Woven fabrics are constructed of interlaced yarns (rovings or bands) usually in a planar structure. Typical glass-fiber fabrics are manufactured by interlacing warp (lengthwise direction) yarns and fill (crosswise direction, also known as weft) yarns on conventional weaving looms (see Figure 3.12). These fabrics can be woven into a variety of structures with exact control over thickness, weight, and strength. The main factors that define a given fabric structure are weave, density of yarns in the fabric, fabric count, characteristics of warp and fill yarn, characteristics of fibers, and factors introduced during weaving, such as yarn crimp. The fabric count refers to the number of warp yarns per inch (ends) and the number of fill yarns per inch (picks). The weave of fabric refers to how warp and fill yarns are interlaced. Weave determines the appearance and some of the handling characteristics of a fabric. Among the most popular weave patterns are plain, twill, crowfoot satin, leno, and unidirectional.

There are two general categories of fabrics used in composites: woven and unidirectional. Woven fabrics combine warp yarns along the major axis and fill yarns across the fabric (Figure 3.12). Unidirectional fabrics have most of the yarns along the warp direction and only nominal fibers in the fill direction to keep the longitudinal fibers in a plane, with specific properties controlled by varying the number of filament ends per inch and type of yarn.

Properties of woven fabric can also affect the type of weave used. Although woven fabrics are more expensive than unidirectional fabrics or tape, significant cost savings can be realized in applications with complex molding operation because labor requirements are reduced. Complex shaped part requiring careful positioning of the reinforcement can benefit from the use of the more workable woven forms of fiber (see Figure 3.13). The plain weave is the most cost-effective of the fabric
types because it has superior stiffness properties and is more open, which is useful when infusing resin. However, the satin (crowfoot or multi-harness) weave provides better draping for conforming to contoured surfaces than plain weave.

**Carbon Fibers**

Compared to glass fibers, carbon fibers have found only limited application in construction. Carbon fibers are characterized by high specific strength, high specific stiffness, and high cost; the first two attributes make these fibers ideal where lightweight is important, such as aerospace applications. Despite the high cost, carbon fiber–based composites have been used in many critical civil infrastructure applications, including seismic rehabilitation, retrofitting, and repair of structural systems such as concrete beams and columns.

This type of fiber is classified as graphite- or carbon-based on the corresponding elemental carbon content. Fibers containing 90% or more elemental carbon are identified as graphite fibers, whereas carbon fibers are those containing 80%–90% elemental carbon—the second type being far more abundant. The carbon content in a fiber is a function of the heat-treatment temperature during processing. The processing temperature also controls the internal structure of the fibers. Carbon fibers are anisotropic with higher strength and stiffness in the longitudinal direction of the fiber compared to the transverse direction. They are composed of small crystallites of turbostratic graphite. In each graphite single crystal, the carbon atoms are arranged in hexagonal arrays, as shown in Figure 3.14. Atoms in the basal planes are held together by strong covalent bonds, while weak van der Waals forces exist.
between layers. This indicates that the basic crystal unit in a fiber is anisotropic. Carbon fibers display a high modulus in the plane of the basal planes, depending on the degree of alignment, and lower modulus transverse to the basal planes in the direction of the van der Waals bonds. Consequently, the longitudinal fiber modulus of elasticity, $E_{fL}$, ranges from 250 to 390 GPa and the transverse fiber modulus of elasticity, $E_{fT}$, ranges from 12 to 20 GPa. High strength of carbon fibers is achieved by good alignment of the basal planes in the fiber direction. Also, the arrangement of layer planes in the cross section influences the transverse and shear properties of the fiber. Figure 3.15 illustrates the cross-sectional structure of several types of carbon fibers. Fiber structure is highly influenced by fabrication method.

Carbon fibers are categorized by fabrication method. Fabrication of carbon fibers involves thermal decomposition (pyrolysis) of the raw material (or precursor). Common precursors for carbon fiber are polyacrylonitrile (PAN), rayon, or pitch, the latter being a complex mixture of thousands of different species of hydrocarbon and heterocyclic molecules. These raw materials are primarily derived from petroleum and asphalt by-products.

To fabricate PAN carbon fibers, first the PAN precursor is spun into a fiber and stretched to produce molecular alignment. The stretched fiber is then heat treated in an oxygen-rich environment. Next, carbonization takes place at 1500°C to drive out non-carbon elements and form a carbon ring structure. Finally, graphitization takes place at 3000°C to convert carbon to turbostratic graphite. The modulus and strength of the fiber depend on this final heat treatment, which governs the crystallite size and alignment. Similar to the fabrication process for glass fibers, the carbon fiber surface is chemically treated with a protective coating and a chemical coupling agent before any further processing. The chemically treated carbon fibers are then wound onto a spool, or in some cases, the matrix is applied to the fibers to produce unidirectional prepregs that can be used in the manufacturing of composite components. These prepregs typically are pre-impregnated with a thermoset and frozen to slow down the setting process.

The pitch fibers are produced by spinning the molten pitch. The orientation of the fibers depends on the spinning conductions. The fibers are oxidized and carbonized at temperatures around 2000°C. Crystal size is greater than in PAN-based fibers. Rayon-based fibers are oriented by stretching during graphitization. Carburized fibers of rayon, pitch, or PAN are stretched during the graphitization stage at very high temperatures. Graphite layers slide over each other and further orient the layers.

Carbon fiber properties can be optimized for a specific application through processing. Type I PAN fibers are graphitized to give maximum stiffness, while Type II PAN fibers are graphitized to give maximum strength. There is a trade-off between strength and stiffness, which is influenced by heat treatment, as shown in Figure 3.16. However, the strength and stiffness of these fibers are well below theoretical values due to poor alignment and flaws introduced during manufacturing. Also, carbon fiber strength has high variability and follows a Weibull distribution. A list of properties for carbon fibers is given in Table 3.6.

![Texture observed in pitch fibers](Radial ~2600°C, Onion-skin (~2600°C), Random (~1200°C))

**FIGURE 3.15** Cross-sectional structure of carbon fibers.
FRP Composite Constituent Materials

Composite carbon fiber reinforcement is available in bundles of individual fibers or filaments called tows, which consists of 12,000 filaments for PAN fibers and 2,000 for pitch fibers. These tows are then stitched together to form a band used in composite fabrication, such as pultrusion, filament winding, or other manufacturing techniques discussed in Chapter 2.

Organic Fibers

Aramid fibers are the best known organic fibers, and of these, Kevlar® (produced by DuPont) is the most commercially recognized brand. Others include Spectra®, Technora, and Twaron. All aramid
fibers are characterized by high toughness, which makes them ideal for impact and ballistic protection applications. It is a low-density fiber offering high strength-to-weight and high stiffness-to-weight ratios. The disadvantages of aramid fibers are similar to those of the parent polymers, namely, low compressive strength, susceptibility to creep, moisture absorption, sensitivity to UV light, temperature-dependent mechanical properties, and high cost.

Organic fibers are produced by an extrusion or spinning process. First, an acid solution of polymer is extruded through a hot die, which has small holes to evaporate the solvent. Next, the polymers are stretched to improve the strength and stiffness. Kevlar is an aromatic polyamide polymer (paraphenylene terephthalamide) with stiff polymer chains that align along the fiber axis in a radial fashion as sheets. Like in the case of carbon fibers, weak bonds exist between sheets. This implies transverse anisotropy, which leads to low compressive strength. Table 3.7 provides a summary of the properties of various grades of Kevlar. Spectra fibers are made from ultralightweight polyethylene by a solution and gel spinning fabrication process, which results in very light, low-density fibers. Unfortunately, these fibers have a low melting point (150°C) with a maximum useful temperature of 100°C. However, the most important property of aramid fibers is their high toughness resulting from their high ductility.

**Organic Fiber Terminology**

Composite Kevlar fiber reinforcement is available in bundles of individual fibers or filaments called ends (or yarns), which consists of 768 filaments. Four yarns are further bundled to form a roving, which are wound onto a spool for packaging. These rovings are then stitched together to form a band used in composite fabrication.

**Comparison of Various Types of Fibers**

In this section, the specific tensile strength, specific modulus, thermal stability, and strain to failure of the various fibers addressed in this section are compared. With respect to compression properties, all fibers have lower compressive strength compared to tensile strength; Kevlar has the lowest compressive strength, while glass typically has the highest.

**Specific Strength and Stiffness**

Figure 3.17 graphically shows plots of the specific strength versus specific stiffness of various fiber types. The data are given in Table 3.8 along with a summary of other important properties. It is clear from Table 3.8 and Figure 3.17 that fibrous materials are much stronger than bulk materials (steel, aluminum, and titanium). More importantly, Figure 3.17 shows that when the properties are

<table>
<thead>
<tr>
<th>Properties</th>
<th>K29</th>
<th>K49</th>
<th>K68</th>
<th>K119</th>
<th>K129</th>
<th>K149</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, ρ (g/cm³)</td>
<td>1.44</td>
<td>1.44</td>
<td>1.44</td>
<td>1.44</td>
<td>1.45</td>
<td>1.47</td>
</tr>
<tr>
<td>Tensile strength, σ_{ult} (GPa)</td>
<td>2.9</td>
<td>3.0</td>
<td>2.8</td>
<td>3.0</td>
<td>3.4</td>
<td>2.4</td>
</tr>
<tr>
<td>Long. elastic modulus, E_{L} (GPa)</td>
<td>70.5</td>
<td>112.4</td>
<td>101</td>
<td>55</td>
<td>100</td>
<td>147</td>
</tr>
<tr>
<td>Diameter, d (μm)</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Long. thermal expansion, α_{L} (10⁻⁶/°C)</td>
<td>-4.0</td>
<td>-4.9</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

FRP Composite Constituent Materials

Steel
Aluminum
Titanium
T300
AS4
IM8
Boron
Kevlar 49
Alumina
S-2 glass
E-glass
Sapphire

0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5
Specific strength (GPa cm$^3$/g)

0 50 100 150 200
Specific stiffness (GPa cm$^3$/g)

FIGURE 3.17 Comparison of specific properties of various materials.

TABLE 3.8
Typical Properties of Fibers$^a$

<table>
<thead>
<tr>
<th>Material</th>
<th>Density, $\rho$ (g/cm$^3$)</th>
<th>Modulus, $E_L$ (GPa)</th>
<th>Poisson’s Ratio, $\nu_L$</th>
<th>Strength, $\sigma_{ult}$ (GPa)</th>
<th>Specific Stiffness, $E/\rho$ (GPa cm$^3$/g)</th>
<th>Specific Strength, $\sigma_{ult}/\rho$ (GPa cm$^3$/g)</th>
<th>Thermal Expansion, $\alpha_L$ ($10^{-6}$/°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>7.80</td>
<td>200</td>
<td>0.32</td>
<td>1.72</td>
<td>25.64</td>
<td>0.22</td>
<td>12.8</td>
</tr>
<tr>
<td>Aluminum</td>
<td>2.70</td>
<td>69</td>
<td>0.33</td>
<td>0.48</td>
<td>25.56</td>
<td>0.18</td>
<td>23.4</td>
</tr>
<tr>
<td>Titanium</td>
<td>4.50</td>
<td>91</td>
<td>0.36</td>
<td>0.76</td>
<td>20.22</td>
<td>0.17</td>
<td>8.8</td>
</tr>
<tr>
<td>AS4$^b$</td>
<td>1.80</td>
<td>235</td>
<td>0.20</td>
<td>3.60</td>
<td>130.56</td>
<td>2.00</td>
<td>−0.8</td>
</tr>
<tr>
<td>T300$^b$</td>
<td>1.76</td>
<td>231</td>
<td>0.20</td>
<td>3.65</td>
<td>131.25</td>
<td>2.07</td>
<td>−0.5</td>
</tr>
<tr>
<td>IM8$^b$</td>
<td>1.80</td>
<td>310</td>
<td>0.20</td>
<td>5.17</td>
<td>172.22</td>
<td>2.87</td>
<td>−1</td>
</tr>
<tr>
<td>Boron</td>
<td>2.60</td>
<td>385</td>
<td>0.21</td>
<td>3.80</td>
<td>148.08</td>
<td>1.46</td>
<td>8.3</td>
</tr>
<tr>
<td>Kevlar 49</td>
<td>1.44</td>
<td>124</td>
<td>0.34</td>
<td>3.62</td>
<td>86.11</td>
<td>2.51</td>
<td>−2.0</td>
</tr>
<tr>
<td>Alumina</td>
<td>3.95</td>
<td>379</td>
<td>0.25</td>
<td>1.58</td>
<td>95.95</td>
<td>0.40</td>
<td>7.5</td>
</tr>
<tr>
<td>S-2 glass</td>
<td>2.46</td>
<td>87</td>
<td>0.23</td>
<td>4.58</td>
<td>35.37</td>
<td>1.86</td>
<td>1.6</td>
</tr>
<tr>
<td>E-glass</td>
<td>2.58</td>
<td>69</td>
<td>0.22</td>
<td>3.45</td>
<td>26.74</td>
<td>1.34</td>
<td>5.4</td>
</tr>
<tr>
<td>Sapphire</td>
<td>3.97</td>
<td>435</td>
<td>0.28</td>
<td>3.6</td>
<td>109.57</td>
<td>0.91</td>
<td>8.8</td>
</tr>
</tbody>
</table>


$^a$ Please note that the sources for the data contained in this chapter include fiber manufacturers’ brochures, the list of references at the end of the chapter, and other industry sources generally available to the public through the Internet. The authors have not performed independent studies to warrant the validity or accuracy of these data. Use caution when using these data for any application. The authors selected the most commonly used products or representative classes of products for this chapter. Our selection of any product does not represent an endorsement on our part.

$^b$ Carbon-based fibers.
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normalized with respect to the density, bulk materials are much heavier than fibrous materials, which is the most important advantage fiber-reinforced composite materials have over traditional materials.

Thermal Stability

Table 3.9 shows the thermal stability of fibers based on the temperature at which the mechanical properties of the fiber start to change drastically, $T_{\text{max}}$. Based on these values, carbon fibers are an excellent choice for high-temperature applications (in an inert atmosphere); however, in the presence of air, carbon starts to oxidize at temperatures above 500°C.

Strain to Failure

Table 3.10 provides the ranges of failure strain for various fiber types with the most ductile behavior displayed by Kevlar fibers followed by glass and carbon. Figure 3.18 shows the stress–strain behavior of various reinforcing fibers.

Particulate Reinforcements

Particulate reinforcements are tiny particles that are near spherical, cubic, or tetragonal in shape. This type of reinforcement is often used as filler in composites in order to reduce the volume of matrix and thereby reduce cost, particularly when matrix costs are greater than the particulate costs. In some cases, particulates are able to enhance the stiffness of the composite. Particulate reinforcement is also available in the form of flakes that are available as platelets made of clay particle or metallic. Flakes typically are used in electrical and heating applications. Particulate reinforcement typically is not used where strength is a critical attribute because the particulates induce stress concentrations that reduce the strength of the composite, unless interface bonds between particulate and matrix are strong.

The primary role of particulate reinforcement is to improve the properties of the matrix. Particulate reinforcement can improve thermal and electrical conductivity of composites, increase wear and

<table>
<thead>
<tr>
<th>TABLE 3.9</th>
<th>Thermal Stability of Fibers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiber</td>
<td>Spectra</td>
</tr>
<tr>
<td>$T_{\text{max}}$ (°C)</td>
<td>100</td>
</tr>
</tbody>
</table>

* If oxygen is present, $T_{\text{max}} = 500°C$.  

<table>
<thead>
<tr>
<th>TABLE 3.10</th>
<th>Strain to Fracture of Fibers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiber</td>
<td>Spectra</td>
</tr>
<tr>
<td>$\varepsilon_{\text{max}}$ (%)</td>
<td>2.9–3.9</td>
</tr>
</tbody>
</table>

abrasion resistance, improve machinability, increase surface hardness, reduce shrinkage, and, most importantly, reduce costs. Discussion on particulate composites will be limited in this chapter since they are typically analyzed with traditional methods for homogeneous, isotropic materials.

**Other Types of Reinforcements**

There are a number of other types of reinforcement materials that have become available recently, including short fibers, whiskers, and nanomaterials. Short fibers (also known as discontinuous fibers) are obtained by chopping continuous fibers or produced directly as short fibers. Short fibers are defined as those with length-to-diameter ratio of less than 10. Short fibers are sometimes randomly oriented in a composite in order to obtain isotropic behavior. Whiskers are elongated single crystals with diameters less than 1 μm and lengths in the order of 100 μm. Whiskers are characterized by high tensile strength and used in ceramic matrix composites and metal matrix composites. Recently, the development of CNTs has introduced an entirely new class of reinforcement for composite applications. These materials are very strong and possess excellent mechanical and electrical properties. One of the primary challenges to their adoption in civil infrastructure is cost. Dispersing these materials in a matrix is also a considerable obstacle and the topic of much current research as of 2012. As the cost of these materials and the technological challenges are resolved, the potential to make a great impact in the construction industry exists—from electromagnetic interference shielding to ballistic-resistant building components.

**REFERENCES**


