REINFORCED CONCRETE DESIGN WITH FRP COMPOSITES

Hota V. S. GangaRao
Narendra Taly
P. V. Vijay

CRC Press
Taylor & Francis Group

REINFORCED CONCRETE DESIGN WITH FRP COMPOSITES

REINFORCED CONCRETE DESIGN WITH FRP COMPOSITES

Hota V. S. GangaRao
Narendra Taly
P. V. Vijay

CRC Press
Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an informa business

CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

Version Date: 20131004

International Standard Book Number-13: 978-1-4200-2019-9 (eBook - PDF)

Visit the Taylor & Francis Web site at
http://www.taylorandfrancis.com

and the CRC Press Web site at
http://www.crcpress.com

Dedication

Advancement of Knowledge — whose illumine recedes all (other) actions to embers

ज्ञानाग्निः सर्वकर्माणि भस्मसात्कुरुते तथा

Bhagawad Gita 4.37

English Pronunciation

GYaanaagniH sarvakarmaaNi bhasmasaatkurute tathaa

Acknowledgment

Author P.V. Vijay wishes to thank his parents, B.S. VenkataRayappa and N. Anjana for their constant encouragement, and his wife Sucharitha and children Aishwarya and Arjun for their patience, support, and sacrifice during the writing of this book. Sincere thanks are also due to several professionals in this field for their valuable suggestions, and to my M.S./Ph.D. graduate students at West Virginia University, where many of the topics in this book have been taught as course materials for the last six years.

Preface

Fiber reinforced polymer (FRP) composites (the combination of two or more materials) have emerged as an evolutionary link in the development of new materials from conventional materials. Used more often in the defense and aerospace industries, advanced composites are beginning to play the role of conventional materials (commodities) used for load-bearing structural components for infrastructure applications. These unique materials are now being used worldwide for building new structures as well as for rehabilitating in-service structures. Application of composites in infrastructural systems on a high-volume basis has come about as a result of the many desirable characteristics of composites that are superior to those of conventional materials such as steel, concrete, and wood.

The increased use of composites in thousands of applications — domestic, industrial, commercial, medical, defense, and construction — has created a need for knowledgeable professionals as well as specific literature dedicated to advancing the theory and design of composites to provide a compendium of engineering principles for structural applications in general and concrete structures in particular.

A rich body of literature — texts and handbooks — exists on composites, such as the manufacturing of composites and the analysis and design of composite lamina based on laminated plate theory. In spite of considerable work that has been carried out over the past 50 years, notably in the U.S., Canada, Japan, and several European countries involving concrete and composites, literature in the form of comprehensive texts that can be practically used for composites in conjunction with concrete construction is sparse.

This book, *Reinforced Concrete Design with FRP Composites*, presents readers with specific information needed for designing concrete structures with FRP reinforcement as a substitute for steel reinforcement and for using FRP fabrics to strengthen concrete members. Separate chapters have been provided that discuss both of these topics exhaustively, supplemented with many practical examples and fundamental theories of concrete member behavior under different loading conditions.

This book is self-contained in that it presents information needed for using FRP composites along with concrete as a building material. It has been written as a design-oriented text and presents in a simple manner the analysis, design, durability, and serviceability of concrete members reinforced with FRP. Mechanics of composites and associated analysis involving differential equations have been intentionally omitted from this book to keep it simple and easy to follow. An extensive glossary of terms has been provided following Chapter 8 for the readers' quick reference.

The idea of writing this book evolved in 1996 while all three authors were attending the Second International Conference on Advanced Composite Materials for Bridges and Structures in Montreal, Canada. Since then, the authors have focused on preparing a state-of-the-art book on analysis and design of concrete members with fiber reinforced polymer reinforcement (bars and fabrics). The material presented in this book is extensively referenced, and based on the authors' extensive research experience of many years and the knowledge-base developed at the Constructed Facilities Center of West Virginia University, Morgantown, West Virginia. In addition to the theory of design of concrete members with FRP bars and fabrics, this book presents an in-depth discussion of the analysis and design approaches recommended by the ACI Committee 440 guide documents.

This book is intended to serve as a text for adoption in colleges and universities teaching a course in concrete design using FRP reinforcement, both as internal reinforcement (as a substitute for steel reinforcement) and as external reinforcement for strengthening concrete members. The authors hope that it will serve as a good resource for practical design, construction, and as a rehabilitation guide for practicing engineers.

Great care has been exercised in organizing and presenting the material in this book; however, readers may inevitably find some controversial ideas and even a few errors. The authors would be grateful to readers for communicating with them any controversies or errors that they might find, and welcome any suggestions or comments offered to enhance the usefulness of this book.

Hota V.S. GangaRao
Narendra Taly
P.V. Vijay

Contents

1 Frequently Asked Questions about Composite Materials

This chapter is intended to present basic concepts of composite materials in a simple, direct, reader-friendly question-and-answer format. Although self-generated, the questions represent the mindset of the uninitiated in that they are frequently asked questions about composite materials. Many topics discussed in the following presentation are discussed in detail in subsequent chapters of this book. Readers will also encounter many new terms related to composites, which are defined in the **Glossary** provided at the end of this book.

What are composite materials?

Composite materials (often referred to as *composites*) are man-made or natural materials that consist of at least two different constituent materials, the resulting composite material being different from the constituent materials. The term composite material is a generic term used to describe a judicious combination of two or more materials to yield a product that is more efficient from its constituents. One constituent is called the *reinforcing* or *fiber phase* (one that provides strength); the other in which the fibers are embedded is called the *matrix phase*. The matrix, such as a cured resin-like epoxy, acts as a binder and holds the fibers in the intended position, giving the composite material its structural integrity by providing shear transfer capability.

The definitions of composite materials vary widely in technical literature. According to Rosato [1982], "a composite is a combined material created by the synthetics assembly of two or more components — a selected filler or reinforcing agent and a compatible matrix binder (i.e., a resin) — in order to obtain specific characteristics and properties…The components of a composite do not dissolve or otherwise merge into each other, but nevertheless do act in concert…The properties of the composite cannot be achieved by any of the components acting alone." Chawla [1987] provides the operational definition of a composite material as one that satisfies the following conditions:

1. It is a manufactured material (not a naturally occurring material, such as wood).

2. It consists of two or more physically or chemically distinct, suitably arranged phases with an interface separating them.
3. It has characteristics that are not depicted by any of the constituents in isolation.

The *EUROCOMP Design Code* [1996] provides a rather technical definition of a composite or composite material as “a combination of high modulus, high strength and high aspect ratio reinforcing material encapsulated by and acting in concert with a polymeric material.” In a practical sense, the term “composite” is thus limited to materials that are obtained by combining two or more different phases together in a controlled production process and in which the content of the dispersed phase in the matrix is substantially large.

Portland cement concretes, and asphalt concretes are examples of man-made composite materials with which civil engineers are familiar. These clearly heterogeneous composites consist of a binding phase (Portland cement phase or asphalt) in which aggregates up to about 1 inch in size are dispersed. The composites used for construction include fiber-reinforced composites, in which fibers are randomly dispersed in cement or polymer matrix, and laminated composites made of a layered structure.

You mentioned wood as being a naturally occurring composite material. Can you explain?

Wood is a composite material that occurs in nature; it is not a manufactured material (hence not generally discussed as a composite). However, it is a composite material in that it consists of two distinct phases: cellulose fibers, and lignin that acts as a binder (matrix) of fibers.

What is meant by plastic?

According to the *EUROCOMP Design Code*, plastic is a material that contains one or more organic polymers of large molecular weight, is solid in its finished state, and can be shaped by flow at some state in its manufacturing, or processing into finished articles.

From a chemistry standpoint, *plastics* are a class of materials formed from large molecules (called *polymers*), which are composed of a large number of repeating units (called *monomers*). The monomers react chemically with each other to form extended molecular chains containing several hundred to several thousand monomer units. Most monomers are organic compounds, and a typical polymer is characterized by a carbon chain backbone, which can be linear or branched. The molecular structure of the unit that makes up very large molecules controls the properties of the resulting material, the polymer or plastic. The rigidity of the chains, density and the regularity of packing (i.e., crystallinity) within the solids, and interaction between the molecular chains can be altered and thus change the bulk properties of the plastic.

Do other composite materials occur naturally?

Bone that supports the weight of body is an example of a naturally occurring composite material. Weight-bearing bone is composed of short and soft collagen fibers that are embedded in a mineral matrix called *apatite*. The human body (Figure 1.1) is an excellent example of a living structure made from composites.

FIGURE 1.1 The human body — an example of a perfect composite structure. (Image by Dorling Kindersley.)

What are some of the most commonly used fiber types?
A variety of fibers are used in commercial and structural applications. Some common types are glass, carbon, aramid, boron, alumina, and silicon carbide (SiC).

How are fibers arranged within a composite?
The arrangement of fibers in a composite is governed by the structural requirement and the process used to fabricate the part.

What determines the mechanical and thermal properties of a composite?
The mechanical and thermal properties of a composite depend on the properties of the fibers, the properties of the matrix, the amount and the orientation of fibers.

What are some common types of matrix materials?
A number of matrix materials are used by the industry (and their number is growing), the more frequently used matrix materials are:

1. Thermoplastic polymers: polyethylene, nylon, polypropylene, polystyrene, polyamids
2. Thermosetting polymers: polyesters, epoxy, phenolic, polymide
3. Ceramic and glass
4. Carbon
5. Metals: aluminum, magnesium, titanium

What are some of the resins used in composites?
Various polymers include epoxy, phenol, polyester, vinyl ester, silicone, alkyd, fluorocarbon, acrylic, ABS (acrylonitrile-butadiene-styrene) copolymer, polypropylene, urethane, polyamide, and polystyrene [Rosato 1982].

Are resins the same as matrix materials?
Yes, but not all matrix materials are resins, as stated earlier. A matrix is a *cured phase* of resin. Fabrics made of fibers such as nylon, polyester, polypropylene, and so on are simple forms of cured resins that have different chemical structures.

Do resins, epoxies, and polymers mean the same thing?
A *resin* is a semisolid or pseudosolid organic material that has often high molecular weight, exhibits a tendency to flow when subjected to stress, and usually has a softening or melting range. In reinforced plastics, the resin is the material used to bind together the fibers. Generally speaking, the polymer with additives is called *resin system* during processing and *matrix* after the polymer has cured (solidified). *Epoxies* are a class of resins (or polymers) that are most commonly used.

How are these resins classified?
Resins (or polymers or plastics) can be classified in several different ways. The earliest distinction between types of polymers was made long before developing any in-depth understanding of their molecular structure; it was based on their reaction to heating and cooling.

On this basis, resins or polymers are classified as *thermoset* (or thermosetting) and *thermoplastic*. From a chemical molecular chain standpoint, the main difference between the two is the nature of bonds between the molecular chains: secondary van der Waals in the thermoplastics and chemical crosslinks in thermosets [Young et al. 1998].

A thermoset resin (or polymer) is characterized by its ability to change into a substantially infusible and insoluble material when cured by the application of heat or by chemical means. Although upon heating, these polymers soften and can be made to flow under stress once, they will not do so reversibly — i.e., heating causes them to undergo a “curing” reaction. Further heating of these polymers leads only to degradation, but it will not soften them. Bakelite is a good example of a thermosetting plastic (polymer or resin). Because Bakelite is a strong material and also a poor conductor of heat and electricity, it is used to make handles for toasters, pots, and pans; for molding common electrical goods, such as wall outlets and adapters; and for such diverse items as buttons and billiard balls. Resins similar to Bakelite are used in fiberboard and plywood.

A thermoplastic resin (or polymer) is characterized by its ability to soften and harden repeatedly by increases and decreases (respectively) in temperature, with minimal change in properties or chemical composition [Mott 2002]. These polymers soften upon heating and can then be made to flow under pressure. Upon cooling, they will regain their solid or rubbery nature. Thermoplastics mimic fats in their response to heat; thermosets are more like eggs (boiled and hardened eggs cannot be transformed back into egg yolks; the change caused by heat is irreversible). Note that thermoplastics lose their properties dramatically after four or five cycles of heating and cooling.

Plastics or polymers can also be classified on the basis of their molecular chains. When molecules are strung together like a string of paper clips, in one or three dimensions, the resulting compound is called a *polymer* or *macromolecule*. One class of polymers consists of linear chains, i.e., the chains extend only in one dimension. These polymers are *linear polymers* and are referred to as thermoplastic. They gradually soften with increasing temperature and finally melt because the molecular chains can move independently. An example is polyethylene, which softens at 85°C. The polymers in the other group have cross-links between chains, so that the material is really one three-dimensional giant molecule — these are called *crosslinked polymers* and referred to as thermosetting [Selinger 1998].

Can you give some examples of thermoset and thermoplastic polymers?

Examples of thermoplastics include ABS, acetals, acrylics, cellulose acetate, nylon, polyethylene, polypropylene, polystyrene, and vinyls. Examples of thermosetting polymers include alkyds, allyls, aminos, epoxies, phenolics, polyesters, silicones, and some types of urethanes.

In addition to acting as binders, do resins serve any other functions?

As mentioned earlier, resin systems used in composites act not only as binders of fibers but also add structural integrity and protection from environmental hazards such as moisture, corrosive agents in the environment, freeze-thaw cycles, and ultraviolet (UV) radiation.

What is meant by resin system?

Typically, resins used in composites are combined with several additives or modifiers (e.g., fillers, catalysts, and hardeners); the term *resin system* rather than resin is used as an all-inclusive term for a binder ready for use at the time of process or manufacturing of a composite. The purpose of these additives is to modify the properties of the resin to provide protection to fibers from moisture ingress and ultraviolet radiation, add color, enhance or reduce translucence, modify surface tension or wettability during the low-viscosity period before curing, and so on.

Why are so many resin systems used in composites?

Different resin systems offer different advantages and also have their own drawbacks. For example, polyester has a low cost and an ability to be made translucent. Its drawbacks include service temperatures below 77°C, brittleness, and a high shrinkage factor of as much as 8% during curing. Phenolics are low-cost resins that provide high mechanical strength but have the drawback of a high void content. Epoxies provide high mechanical strength and good adherence to metals and glasses, but high costs and processing difficulties are their drawbacks. Thus, each resin system offers some advantages but also has some limitations. The use of a particular resin system depends on the application.

Are many kinds of composites used? How are they classified?

Composites are classified generally in one of the two ways [Kaw 1997]: (1) by the geometry of reinforcement — particulate, flake, and fibers; or (2) by the type of matrix — polymer, metal, ceramic, and carbon. *Particulate* composites consist of particles immersed in matrices such as alloys and ceramics. *Flake* composites consist of flat fiber reinforcement of matrices. Typical flake materials are glass, mica, aluminum, and silver. These composites provide a high out-of-plane modulus, higher strength, and lower cost. Fiber composites consist of a matrix reinforced by short (discontinuous) or long (continuous) fibers and even fabrics. Fibers are generally anisotropic, such as carbon and aramid.

What is meant by reinforced plastic?

Reinforced plastic is simply a plastic (or polymer) with a strength greatly superior to those of the base resin as a result of the reinforcement embedded in the composition [Lubin 1982].

What are FRPs?

"FRP" is an acronym for *fiber reinforced polymers*, which some also call fiber reinforced plastics, so called because of the fiber content in a polyester, vinyl ester, or other matrix. Three FRPs are commonly used (among others): composites containing glass fibers are called *glass fiber reinforced polymers* (GFRP); those containing carbon fibers are called *carbon fiber reinforced polymers* (CFRP); and those reinforced with aramid fibers are referred to as *aramid fiber reinforced polymers* (AFRP).

You referred to FRP as fiber reinforced polymer. How is this different from fiber reinforced plastic?

Actually, there is no difference. *Plastics* are composed of long chain-like molecules called *polymers*. The word "polymer" is a chemistry term (meaning a high molecular weight organic compound, natural or synthetic, containing repeating units) for which the word "plastic" is used as a common descriptive. The word "polymer" rather than "plastic" is preferred in the technical literature. However, the term "fiber reinforced plastics" continues to enjoy common usage because of the physical resemblance of the FRPs to commonly used plastics. The term "FRP" is most often used to denote glass fiber reinforced polymers (or plastics). The term "advanced composites" is usually used to denote high-performance carbon or aramid fiber-reinforced polymers (or plastics).

Are FRPs different from regular plastics that are used for making common products such as plastic bottles, jugs, spoons, forks, and bags (i.e., grocery and trash bags)? What is the difference?

FRPs are very different from ordinary plastics; the key phrase in FRP is "fiber reinforced." Generally, plastic is a material that is capable of being shaped into any

FIGURE 1.2 Common household plastic products.

form, a property that has made it a household name. Figure 1.2 shows a variety of unreinforced plastic products, such as a milk jug, coffee maker, bottles to contain medicine and liquids, compact disc, plastic bags, and other items found in common households. Literally hundreds of thousands of unreinforced plastic products are in use all over the world. These include our packing and wrapping materials, many of our containers and bottles, textiles, plumbing and building materials, furniture, flooring, paints, glues and adhesives, electrical insulation, automobile parts and bodies, television, stereo, and computer cabinets, medical equipment, cellular phones, compact discs, and personal items such as pens, razors, toothbrushes, hair-sprays, and plastic bags of all kinds. In fact, we can say that we live in the Plastic Age (similar to the prehistoric Stone Age).

Can you describe some of these plastics and their commercial uses?

Table 1.1 lists several commercial and industrial applications of plastics along with desirable properties pertinent to those applications and suitable plastics. Some of these plastics are categorized as hard and tough — they have high tensile strength and stretch considerably before breaking. Because of these superior properties, they are relatively expensive and have specialized applications. For example, consider *polyacetals*, which have high abrasion resistance and resist organic solvents and water. Therefore, they are used in plumbing to replace brass or zinc in showerheads, valves, and so on. Furniture castors, cigarette lighters, shavers, and pens are also often made from polyacetals as they give a nonstain as well as satin finish.

TABLE 1.1
Major Types of Commercial Plastics and Applications

Type of Plastic	Characteristics	Typical Commercial Applications
Low-density polyethylene (LDPE)	Low melting; very flexible; soft; low density	Bags for trash and consumer products; squeeze bottles; food wrappers; coatings for electrical wires and cables
Poly(vinyl chloride), also known as PVC	Tough; resistant to oils	Garden hoses; inexpensive wallets, purses, keyholders; bottles for shampoos and foods; blister packs for various consumer products; plumbing, pipes, and other construction fixtures
High-density polyethylene (HDPE)	Higher melting, more rigid, stronger, and less flexible than low-density polyethylene	Sturdy bottles and jugs, especially for milk, water, liquid detergents, engine oil, antifreeze; shipping drums; gasoline tanks; half to two-thirds of all plastic bottles and jugs are made of this plastic
Polypropylene	Retains shape at temperatures well above room temperature	Automobile trim; battery cases; food bottles and caps; carpet filaments and backing; toys
Polystyrene	Lightweight; can be converted to plastic foam	Insulation; packing materials including "plastic peanuts"; clear drinking glasses; thermal cups for coffee, tea, and cold drinks; inexpensive tableware and furniture; appliances; cabinets
Poly(ethylene terephthalate), also known as PET	Easily drawn into strong thin filaments; forms an effective barrier to gases	Synthetic fabrics; food packages; backing for magnetic tapes; soft-drink bottles
Phenol-formaldehyde resins	Strongly adhesive	Plywood; fiberboard; insulating materials
Nylon, phenolics, tetrafluoroethylene (TFE)-filled acetals	Easily drawn into strong thin filaments; resistant to wear, high tensile and impact strength, stability at high temperatures, machinable	Synthetic fabrics; fishing lines; gears and other machine parts
Tetrafluoroethylene (TFE) fluorocarbons, nylons, acetals	Low coefficient of friction; resistance to abrasion, heat, corrosion	High-strength components, gears, cams, rollers
Acrylics, polystyrene, cellulose, acetate, vinyls	Good light transmission in transparent and translucent colors, formability, shatter resistance	Light-transmission components

Source: Adapted from Selinger, B., *Chemistry in the Market Place*, 5th ed., Marrickville, NSW, Australia: Harcourt Brace & Co. Australia, 1998; Snyder, C.H., *The Extraordinary Chemistry of Ordinary Things*, New York: John Wiley & Sons, 2003.

Polycarbonate is an example of a plastic that finds use in a wide variety of commercial applications. Polycarbonates are often used instead of glass because they are transparent, dimensionally stable, and impact resistant, even when subjected to a wide range of temperatures. Babies' bottles, bus-shelter windows, plastic sheeting for roofing, and telephones are examples of polycarbonates. In sporting equipment, they are used in helmets for team players, motorcyclists, and snowmobilers. Because of their superior fire resistance, they are used in firemen's masks, interior moldings of aircraft, and in electronic equipment [Selinger 1998].

Nylon is yet another example of plastic that has excellent mechanical properties and resists solvents. As such, it is an ideal material for gears and bearings that cannot be lubricated. About 50% of molded nylon fittings go into cars in the form of small gears (for wipers), timing sprockets, and all sorts of clips and brackets.

What are advanced composites and high-performance composites?

Fiber reinforced composites are composed of fibers embedded in a matrix. The fibers can be short or long, continuous or discontinuous, and can be oriented in one or multiple directions. By changing the arrangements of fibers (which act as reinforcement), properties of a composite can be engineered to meet specific design or performance requirements. A wide variety of fibers, such as glass, carbon, graphite, aramid, and so on, are available for use in composites and their number continues to grow.

An important design criterion for composites is the performance requirement. In low-performance composites, the reinforcements — usually in the form of short or chopped fibers — provide some stiffness but very little strength; the load is carried mainly by the matrix. Two parameters that are used to evaluate the high-performance qualities of fibers are *specific strength* and *specific stiffness*. Fibers having high specific strength and high specific stiffness are called *advanced* or *high-performance fibers* and were developed in the late 1950s for structural applications. Composites fabricated from advanced fibers of thin diameters, which are embedded in a matrix material such as epoxy and aluminum, are called *advanced* or *high-performance composites*. In these composites, continuous fibers provide the desirable stiffness and strength, whereas the matrix provides protection and support for the fibers and also helps redistribute the load from broken to adjacent intact fibers. These composites have been traditionally used in aerospace industries but are now being used in infrastructure and commercial applications. The advanced composites are distinguished from *basic composites*, which are used in high-volume applications such as automotive products, sporting goods, housewares, and many other commercial applications where the strength (from a structural standpoint) might not be a primary requirement.

What is meant by specific strength and specific stiffness? What is their significance?

Specific strength is defined as the ratio of the tensile strength of a material to its unit weight. *Specific stiffness* (also called *specific modulus*) is defined as the ratio of the modulus of a material to its unit weight. These properties are often cited as indicators of the structural efficiency of a material; they form very important and often critical design considerations for the many products for which composites offer unique advantages.

TABLE 1.2
Properties of Selected Composites and Steel

Material	Tensile Strength (ksi)	Modulus of Elasticity ($\times 10^6$ psi)	Specific Weight, γ (lb/in^3)	Specific Strength ($\times 10^6$ in)	Specific Modulus ($\times 10^8$ in)
Steel					
AISI 1020 HR	55	30.0	0.283	0.194	1.06
AISI 5160 OQT 700	263	30.0	0.283	0.929	1.06
Aluminum					
6061-T6	45	10.0	0.098	0.459	1.02
7075-T6	83	10.0	0.101	0.822	0.99
Titanium					
Ti-6A1-4V quenched and aged at 1000°F	160	16.5	0.160	1.00	1.03
Glass/epoxy composite					
60% fiber content	114	4.0	0.061	1.87	0.66
Boron/epoxy composite					
60% fiber content	270	30.0	0.075	3.60	4.00
Graphite/epoxy composite					
62% fiber content	278	19.7	0.057	4.86	3.45
Graphite/epoxy composite					
Ultrahigh modulus	160	48.0	0.058	2.76	8.28
Aramid/epoxy composite					
60% fiber content	200	11.0	0.050	4.00	2.20

Source: Adapted from Mott, R.L. *Applied Strength of Materials,* Upper Saddle River, NJ: Prentice Hall, 2002.

Can you list a few important mechanical properties of composites and metals such as steel and aluminum to make a valid comparison and explain why composites are considered superior structural materials?

Table 1.2 lists several key properties (tensile strength, modulus of elasticity, specific weight, specific strength, and specific modulus) of metals such as steel, aluminum, titanium alloys, and selected composites [Mott 2002]. It also lists the two important parameters — specific strength and specific stiffness — that are often cited as indicators of structural efficiency of a material.

What does this information mean to a designer?

The information provided in Table 1.2 is very important to a designer while selecting a material type for complex structural systems. Figure 1.3 gives a comparison of the specific strength and specific stiffness of selected composite materials [Mott 2002].

For example, consider a boron/epoxy composite having a specific weight of 0.075 and steel (AISI 5160 OQT 700) having a specific weight of 0.283; their strengths are comparable — 270 ksi and 263 ksi, respectively. However, the specific strength of the boron/epoxy composite (3.60) is almost four times that of steel

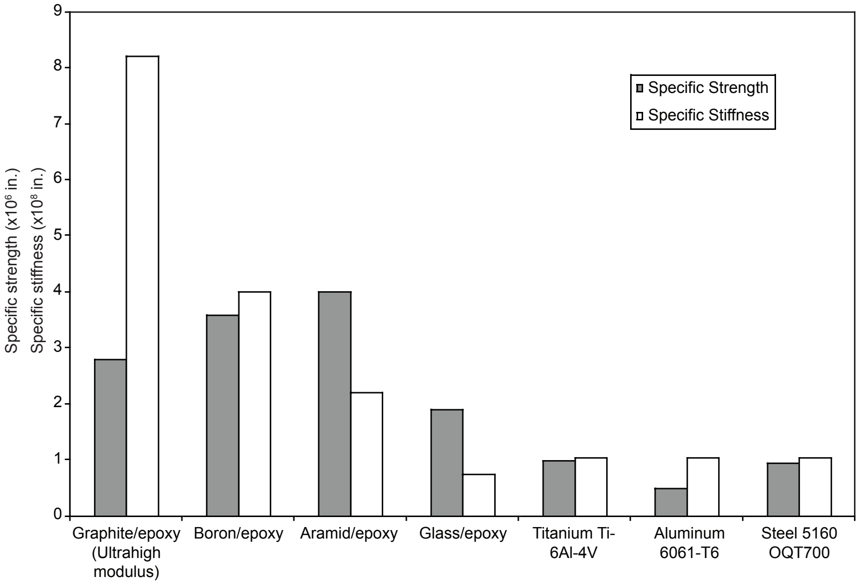

FIGURE 1.3 Comparison of specific strength and specific stiffness of selected materials. (Adapted from Mott, R.L. *Applied Strength of Materials,* Upper Saddle River, NJ: Prentice Hall, 2002.)

(0.929). Now consider the simple case of a rod designed to carry an axial tensile force. The cross-section of the boron/epoxy composite rod need only be one-fourth that of a steel rod. This reduction in cross-sectional area translates into reduced space requirements and also reduced material and energy costs. Figure 1.4 shows a plot of these data with specific strength on the vertical axis and specific modulus on the horizontal axis [Mott 2002]. Note that when weight is critical, the ideal material would be found in the upper right part of Figure 1.4.

Can you describe the basic anatomy of composites?

As stated earlier, the two main constituents of composites are fibers and resins. Additionally, they contain quantities of other substances known as *fillers* and *additives*, ranging from 15 to 20% of the total weight (and hence the term *resin system*). Fibers are the backbone of a composite. Their diameters are very thin — much thinner than a human hair. For reasons explained earlier, their small diameter is the reason for their extreme strength. The tensile strength of a single glass filament is approximately 500 ksi. However, the thin diameter of a fiber is also a major disadvantage in that the compressive strength of a thin fiber is very small due to its vulnerability to buckling.

To harness the strength of fibers, they are encased in a tough polymer matrix, which gives the composite its bulk. The matrix serves to hold fibers together in a structural unit and spread the imposed loads to many fibers within the composite, and to protect the fibers from environmental degradation attributed to moisture,

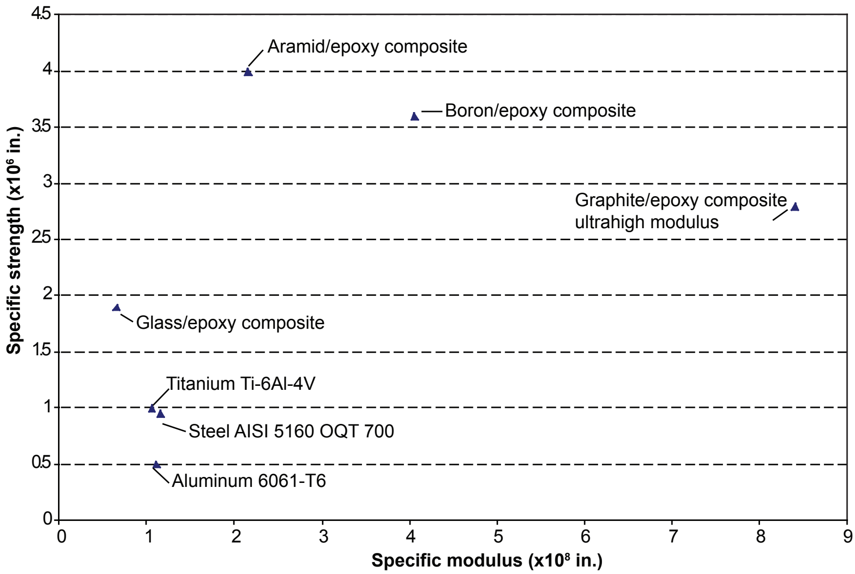

FIGURE 1.4 Specific strength vs. specific modulus for selected metals and composites (Adapted from Mott, R.L. *Applied Strength of Materials,* Upper Saddle River, NJ: Prentice Hall, 2002.)

ultraviolet rays, corrosive chemicals, and to some extent, susceptibility to fire and from damage to fibers during handling. The function of the matrix is somewhat analogous to that of concrete in a conventional reinforced concrete member wherein the concrete surrounding reinforcing bars maintains the alignment and position of bars, spreads (or distributes) the imposed loads to all the reinforcing bars present in the member, and also provides environmental and fire protection to the bars. However, a major difference is noted. In a reinforced concrete member, concrete itself also shares the imposed loads (e.g., in beams and columns), whereas in a composite the matrix shares a negligible amount of load but helps transfer the load to fibers through interlaminar and in-plane shear; the entire imposed load is taken practically by the fibers alone.

The third constituent — fillers — are particulate materials whose major function is not to improve the mechanical properties of the composite but rather to improve aspects such as extending the polymer and reducing the cost of the plastic compound (fillers are much less expensive than the matrix resin). One of the earliest examples of filler is wood flour (fine sawdust), long used in phenolics and other thermosets. Calcium carbonate is used in a variety of plastics. Polypropylene is often filled with talc [Rosen 1993]. Hollow glass spheres are used to reduce weight. Clay or mica particles are used to reduce cost. Carbon particles are used for protection against ultraviolet radiation.

Alumina trihydrate is used for flame and smoke suppression [Katz 1978]. Fillers can also be used to improve certain properties of plastics. They almost all reduce mold shrinkage and thermal expansion coefficients, and also reduce warpage in molded parts. Mica and asbestos increase heat resistance.

In addition to the above described three constituents, *coupling agents* are used to improve the fiber surface wettability with the matrix and create a strong bond at the fiber-matrix interface. For example, coupling agents are used with glass fibers to improve the fiber-matrix interfacial strength through physical and chemical bonds and to protect them from moisture and reactive fluids [Mallick 1993]. The most common coupling agents are silanes.

For maximum fiber efficiency, stress must be efficiently transferred from the polymer to the reinforcing agents. Most inorganics have *hydrophilic* surfaces (i.e., they have an affinity for absorbing, wetting smoothly with, tending to combine with, or capable of dissolving in water), while the polymers are *hydrophobic* (i.e., incapable of dissolving in water), which results in a poor interfacial adhesion. This problem is exacerbated by the tendency of many inorganic fibers — particularly glass — to absorb water, which further degrades adhesion [Rosen 1993]. Carbon fiber surfaces are chemically inactive and must be treated to develop good interfacial bonding with the matrix. Similarly, Kevlar 49 fibers also suffer from weak interfacial adhesion with most matrixes [Mallick 1993].

Other constituents are added to composites in minute quantities for various important reasons. Most polymers are susceptible to one or more forms of degradation, usually as a result of environmental exposure to oxygen or ultraviolet radiation, or to high temperatures during processing. *Stabilizers* are added to inhibit degradation of polymers.

Plastics are often colored by the addition of pigments, which are finely powdered solids. If the polymer is itself transparent, a pigment imparts opacity. A common pigment is titanium dioxide, which is used where a brilliant, opaque white is desired. Sometimes pigments perform other functions as well. An example is calcium carbonate, which acts both as a filler and a pigment in many plastics. Black carbon is another example that acts both as a stabilizer and a pigment.

Dyes are another constituent used in minute quantities in producing plastics. Dyes are colored organic chemicals that dissolve in the polymer to produce a transparent compound, assuming that the polymer is transparent to begin with [Rosen 1993].

Flammability of polymers is a serious concern when designing with composites. Being composed of carbon and hydrogen, most synthetic polymers are flammable. Flame-retardants are added to polymers to reduce their flammability. The most common flame-retarding additives for plastics contain large proportions of chlorine or bromine [Rosen 1993]; however nonhalogenated flame retardants (other than chlorine or bromine) are being researched and implemented actively.

What are the major considerations when designing with reinforcing fibers?

Composites are engineered materials for which fibers and resins are selected based on their intended function. Selection of appropriate fibers and resins are two major engineering decisions to be made in designing composites.

Generally speaking, three considerations must be met when designing with fiber reinforcement:

1. Fiber type: glass, carbon, aramid, or others
2. Fiber form: roving, tow, mat, woven fabrics, or others
3. Fiber architecture, i.e., orientation of fibers

The fiber architecture or fiber orientation refers to the position of the fiber relative to the axes of the element. Fibers can be oriented along the longitudinal axis of the element (at 0° to the longitudinal axis), transverse to the longitudinal axis (at 90° to the longitudinal axis), or in any other direction at the designer's discretion to achieve optimum product efficiency. This customization flexibility is unique to the fabrication of composites, which gives them versatility in applications. Although fiber orientation in a composite can be so varied that the resulting product is virtually an isotropic material with equal strength in all directions, in most cases composite structural elements are designed with the greatest strength in the direction of the greatest load. For example, for composite reinforcing elements such as bars and tendons, fibers are oriented longitudinally (i.e., in the direction of the applied or anticipated tensile force).

Once the fiber type and orientation are determined, an appropriate resin and the fiber-resin volume ratio are selected. The strength of a composite depends on the fiber-resin volume ratio — the higher the ratio, the stronger and lighter the resulting composite. Of course, higher fiber content results in increased product cost, especially for composites containing carbon and aramid fibers, including process difficulties.

Production of composites is amenable to a variety of processes, which can be fully automated or manual. Automated processes involve production of composites completely in a factory. Manually, the fibers and resin can be combined and cured on site. *Pultruded products* (so called because they are produced through a mechanical process called *pultrusion*) such as various structural shapes (e.g., beams, channels, tubes, bars) are examples of composites that are produced in a factory in their entirety and the finished products shipped to sites for the end use. Other automated processes for producing composites for construction applications include filament winding and molding. Filament winding can take place at a plant facility or at a construction site. Molding processes (several kinds exist) are also used in a plant facility. Alternatively, for low-volume applications such as structural repair and retrofit, fibers and resins can be mixed and cured on site, a manual process referred to as *hand-* or *wet-lay up* systems. In all cases, the fiber reinforcing material must be completely saturated with resin, compacted to squeeze out excess resin and entrapped air bubbles, and fully cured prior to applying loads. A variation of wet-lay up system is "prepreg" (short for pre-impregnated), which consists of unidirectional fiber sheets or fabrics that are pre-impregnated (i.e., precoated) with a resin system and ready for application on site. Machine applied systems are also available but are not commonly used because of the complexities of field applications.

You alluded to the term "pultrusion." What does this mean?

The term *pultrusion* refers to a continuous, mechanical process (see Figure 1.5) for manufacturing composites that have uniform cross-sectional shapes — such as "I,"

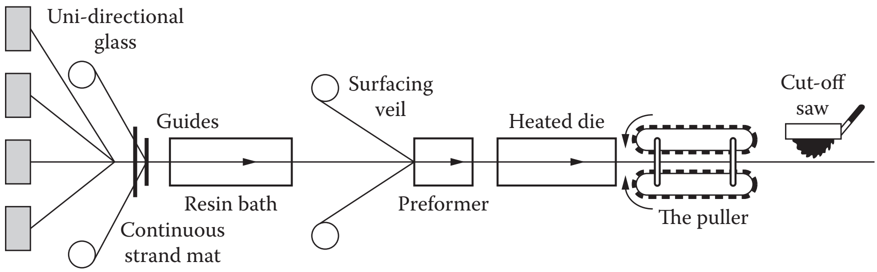

FIGURE 1.5 Schematic of pultrusion process. (Courtesy of Strongwell Corporation, Bristol, VA.)

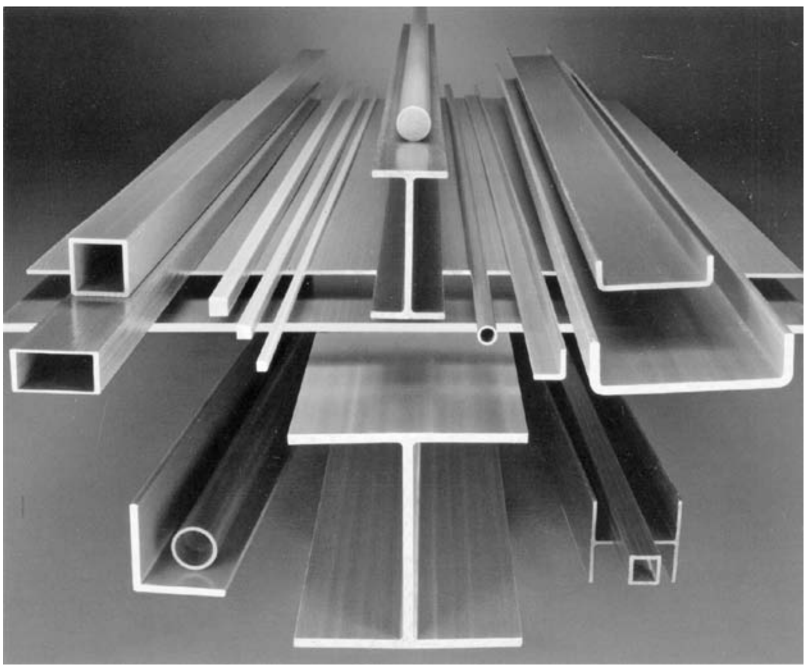

FIGURE 1.6 Fiberglass composite structural elements formed by pultrusion. (Courtesy of Strongwell Corporation, Bristol, VA.)

"L," "T," rectangular, and circular sections — and hollow rectangular and circular tubes (similar to steel shapes) as shown in Figure 1.6 The process is automated; it involves pulling a fiber-reinforcing material through a resin bath and then through a heated (shaping) die where the resin is cured. Pultrusion is a cost-effective production process and is the dominant manufacturing process used for producing structural shapes, reinforcing bars, and prestressing tendons.

What are the main types of fibers used for producing composites and on what basis are they selected?

Composites used for civil engineering applications are produced typically from three types of fibers: glass, carbon, and aramid. The selection of fiber type depends on the specific needs for a particular structural application. Various factors important for a composite design include the required strength, stiffness, corrosion resistance, durability, and cost. Cost is a major consideration and often plays a pivotal role in the selection process. Glass fibers are the least expensive. Carbon fibers are much more expensive than glass fibers, and aramid fibers are the most expensive. Typically, these fibers can cost several dollars per pound; some cost as high as $30 per pound in the year 2005. By comparison, structural steel in the year 2005 cost approximately $0.50 to $1.00 per pound. Considerable cost differences are found in terms of composite types, i.e., glass composite vs. carbon composite vs. aramid composite.

Can you describe various types of fibers?

Let us briefly discuss three types of commonly used fibers: glass, carbon, and aramid. The quality of these fibers in terms of greater strength and corrosion resistance continues to improve as new technologies evolve.

Glass fibers are produced from silica-based glass compounds that contain several metal oxides. A variety of glass fibers are produced to suit specific needs. The *E-glass* (E stands for electrical), so called because its chemical composition gives it excellent insulation properties, is one of the most commonly used glass fibers because it is the most economical. *S-glass* (S stands for structural) offers greater strength (typically 40% greater at room temperature) and also greater corrosion resistance than provided by E-glass. The corrosion-resistant *E-CR glass* provides even better resistance to corrosive materials such as acids and bases.

Carbon (and graphite, the two terms are often used interchangeably) fibers are produced from synthetic fibers through heating and stretching. Polyacrylonitrile (PAN), pitch (a by-product of the petroleum distillation process), and rayon are the three most common precursors (raw materials) used for producing carbon fibers. Some of these fibers have high strength-to-weight and modulus-to-weight ratios, high fatigue strength, and low coefficient of thermal expansion, and even negative coefficient of thermal expansion.

Aramid fiber is an aromatic polyamide that provides exceptional flexibility and high tensile strength. It is an excellent choice as a structural material for resisting high stresses and vibration.

What is Kevlar?

Kevlar® is the trademarked name for the aramid fiber produced by the DuPont Company.

In what forms are various fibers commercially available?

An individual fiber of indefinite length used in tows, yarns, or rovings is called *filament*. Because of their small diameters, filaments are extremely fragile, the primary reason for which they are sold in bundles. The industry uses different terminology for describing bundles of filaments that is based on the fiber type. For example, glass and aramid fibers are called *strands*, *rovings*, or *yarns*. The term *strands* refers to a collection of continuous glass or aramid filaments, whereas the term *rovings* refers to a collection of untwisted strands. Untwisted carbon strands are called *tows*. The term *yarns* refers to a collection of filaments or strands that are twisted together. Carbon fiber is commercially available as "tow," i.e., a bundle of untwisted fiber filaments. For example, 12K tow has 12,000 filaments and is commonly sold in a variety of modulus categories: standard or low (33 to 35 msi), intermediate (40 to 50 msi), high (50 to 70 msi), and ultra-high (70 to 140 msi).

Fibers for infrastructure applications are most commonly supplied in the form of rovings, tows, and fabrics. Both tows and rovings can be used to produce a wide variety of reinforcing materials such as mats, woven fabrics, braids, knitted fabrics, preforms, and hybrid fabrics. *Mats* are nonwoven fabrics that provide equal strength in all directions. They are available in two forms: chopped and continuous strand. Chopped-strand mats are characterized by randomly distributed fibers that are cut to lengths ranging from 1.5 to 2.5 in. Continuous-strand mats are formed by swirling continuous-strand fiber onto a moving belt and finished with a chemical binder that serves to hold fibers in place. Continuous-strand mat is stronger than the chopped-strand mat. Because of its higher strength, continuous-strand mat is used in molding and pultrusion processes. Chopped-strand mat is relatively weaker than the continuous-strand mat but is relatively cheaper.

Fabricated on looms, woven fabrics are available in a variety of weaves, widths, and weights. Bidirectional woven fabrics provide good strength in 0° and 90° directions and are suitable for fast fabrication. A disadvantage with woven fabrics is that fibers get crimped as they pass over and under each other during weaving, which results in a lower tensile strength of the fabric. Hybrid fabrics are manufactured with different fiber types.

Braided materials are produced by a complex manufacturing process. Although they are more efficient and stronger than woven fabrics, they cost more. Braided materials derive their higher strength from three or more yarns intertwined with one another without twisting any tow yarns around each other. Braids are continuously woven on the bias and have at least one axial yarn that is not crimped in the weaving process. Braided materials can be flat or tubular. Flat braids are used primarily for selective reinforcement (e.g., strengthening specific areas in pultruded parts), whereas tubular braids are used to produce hollow cross-sections for structural tubes.

Knitted fabrics permit placement of fibers exactly where they are needed. They are formed by stitching layers of yarn together, which permits greater flexibility in yarn alignment as the yarns can be oriented in any desired direction by putting them atop one another in practically any arrangement. A major advantage of knitted fabrics is the absence of crimping in the yarns as they lay over one another rather than crossing over and under one another (as in the case of woven fabrics). The absence of yarns' crimping results in utilization of their inherent strength, and helps create a fabric that is more pliable than woven fabrics.

What is so special about composites? What is wrong with using the conventional materials such as steel, concrete, aluminum, and wood?

Nothing is wrong with using the conventional building materials such as steel, concrete, aluminum, and wood. However, for certain applications, composite materials offer an attractive, and often the preferred, alternative because of the many properties that are superior to those of conventional building materials. Composites evolved as more efficient structural materials because of their many superior properties: ultra-high strength, corrosion resistance, lightweight, high fatigue resistance, nonmagnetic, high impact resistance, and durability. Because composites are man-made materials, they can be engineered (i.e., their shapes or profiles can be produced at designer's discretion) to meet the needs of specific applications. Structures built with composites also have low life-cycle costs.

REFERENCES AND SELECTED BIBLIOGRAPHY

Ball, P., *Designing the Molecular World*, Princeton, NJ: Princeton University Press, 1994.

Benjamin, B.S., *Structural Design with Plastics*, New York: Van Nostrand Reinhold Co., 1982.

CFI, *Composites for Infrastructure*, Wheatridge, CO: Ray Publishing, 1998.

Chawla, K.K., *Composite Materials: Science and Engineering*, New York: Springer-Verlag, 1987.

Emsley, J., *Molecules at an Exhibition*, Oxford: Oxford University Press, 1998.

EUROCOMP, Structural design of polymer composites, in *EUROCOMP Design Code and Handbook*, J.L. Clarke (Ed.), London: E & FN Spon, 1996.

Gay, D., Hoa, S.V., and Tsai, S.W., *Composite Materials: Design and Applications*, Boca Raton, FL: CRC Press, 2003.

Harper, C.A. and Petrie, E.M., *Plastic Materials and Processes: A Concise Encyclopedia*, New York: Wiley Interscience, 2003.

Herakovich, C.T., *Mechanics of Fibrous Composites*, New York: John Wiley & Sons, 1998.

Hollaway, L.C. and Leeming, M.B., *Strengthening of Reinforced Concrete Structures Using Externally-Bonded FRP Composites in Structural and Civil Engineering*, Boca Raton, FL: CRC Press, 1999.

Katz, H.S. and Milewski, J.V. (Eds.), *Handbook of Fillers and Reinforcements for Plastics*, New York: Van Nostrand Reinhold Co., 1978.

Kaw, A.K., *Mechanics of Composites Materials*, Boca Raton, FL: CRC Press, 1997.

Lubin, G. (Ed.), *Handbook of Composites*, New York: Van Nostrand Reinhold Co., 1982.

Mallick, P.K., *Fiber Reinforced Composite Materials: Manufacturing and Design*, New York: Marcel Dekker, 1993.

Marshall, A., *Composite Basics Seven*, Walnut Creek, CA: Marshall Consulting Co., 2005.

McCrum, N.G., Buckley, C.P., and Bucknall, C.P., *Principles of Polymer Engineering*, New York: Oxford University Press, 1988.

Miller, T.E. (Ed.), *Introduction to Composites*, 4th ed., New York: Composites Institute of the Society of Plastics Industry, 1997.

Mott, R.L., *Applied Strength of Materials,* Upper Saddle River, NJ: Prentice Hall, 2002.

Potter, K., *An Introduction to Composite Products*, New York: Chapman & Hall, 1997.

Rosato, D.V., An overview of composites, in *Handbook of Composites*, G. Lubin (Ed.), New York: Van Nostrand Reinhold Co., 1982.

Rosen, S., *Fundamental Principles of Polymeric Materials*, New York: John Wiley & Sons, 1993.

Schwartz, M., *Composites Materials Handbook*, 2nd ed., New York: McGraw-Hill Co., 1992.

Selinger, B., *Chemistry in the Market Place*, 5th ed., Marrickville, NSW, Australia: Harcourt Brace & Co. Australia, 1998.

Snyder, C.H., *The Extraordinary Chemistry of Ordinary Things*, New York: John Wiley & Sons, 2003.

Young, J.F., Mindess, S., Gray, R.J., and Bentur, A., *The Science and Technology of Civil Engineering Materials*, Upper Saddle River, NJ: Prentice Hall, 1998.

2 Properties of Constituent Materials: Concrete, Steel, Polymers, and Fibers

2.1 INTRODUCTION

Development of composite materials represents a milestone in the history of our civilization. Along with conventional building materials such as steel, concrete, aluminum, and wood, composite materials offer an excellent alternative for a multitude of uses. Use of composite materials was pioneered by the aerospace industry beginning in the 1940s, primarily because of the material's high-performance and lightweight qualities. Today their potential is being harnessed for many uses. Advanced composite materials — so called because of their many desirable properties, such as high-performance, high strength-to-weight and high stiffness-to-weight ratios, high energy absorption, and outstanding corrosion and fatigue damage resistance — are now increasingly used for civil engineering infrastructure such as buildings and bridges.

Composite materials are manufactured from two or more distinctly dissimilar materials — physically or chemically — that are suitably arranged to create a new material whose characteristics are completely different from those of its constituents. Basically, composites consist of two main elements: the structural constituent, which functions as the load carrying element, and the body constituent called *matrix*, which encloses the composite. The structural constituent can be in the form of fibers, particles, laminae (or layers), flakes, and fillers. The matrix performs important dual functions: It acts as a binder to hold the fibrous phase in place (i.e., holds the fibers in a structural unit) protecting fibers from environmental attack, and under an applied load, it deforms and distributes the load to the high modulus fibers.

Composites discussed in this book are those fabricated from fibers such as glass, carbon, aramid, and boron. Unlike materials such as steel and aluminum alloys, fiber composites are anisotropic, hygrospic, and hygrothermally sensitive. The mechanical properties of a composite that influence its behavior and performance as structural material depend on the properties of its constituent — fibers and matrix — and the process used for its manufacture. Understanding these properties is very important for proper application of the composite. This chapter discusses the properties of various matrixes and fibers and methods of manufacturing carbon and glass fibers.

In addition to using composites for stand-alone load-carrying components (such as prefabricated bridge modules, beams, and girders), they can be also used in conjunction with concrete and steel as load-sharing elements. For example, glass fiber reinforced polymer (GFRP) bars can be used as reinforcement for concrete members in lieu of conventional steel reinforcing bars. Prestressing bars and strands made from carbon fibers can be used as tendons for prestressed concrete construction. This type of application is commonly referred to as *internal reinforcement*. Similarly, carbon fiber reinforced polymer (CFRP) strips can be used as *external reinforcement* for increasing the load-carrying capacity of conventional steel and reinforced concrete beams. In this type of application, the CFRP strips are bonded to the exterior tensile face of a beam to complement its flexural capacity. A brief discussion of properties of concrete and reinforcing steel is presented in this chapter. Although these properties are discussed in the many texts on design of reinforced concrete and steel structures, they are briefly reviewed in this chapter to preserve completeness of the subject matter.

2.2 INGREDIENTS OF CONCRETE

Concrete is a composite material consisting of fine and coarse aggregates and a binding material formed from a mixture of hydraulic cement and water. Admixtures or additional ingredients can also be used to alter the properties of concrete. ACI 318-02 defines concrete as "a mixture of portland cement or any other hydraulic cement, fine aggregate, coarse aggregate, and water with or without admixtures" [ACI 318-02]. The properties of concrete so formed are entirely different from any of its constituent materials, and that qualifies concrete as a composite material.

2.2.1 Aggregates

The term *aggregate* refers to the granular material, such as crushed stone, sand, or blast-furnace slag. Aggregates form the bulk of the finished concrete product. To broadly differentiate between the particle sizes of the aggregate, the latter is divided into two categories: *coarse aggregate* and *fine aggregate*. The particle sizes are referenced to the sieve number. The coarse aggregate (e.g., gravel) refers to the particle sizes larger than 4.75 mm (i.e., not passing through a No. 4 sieve). The fine aggregate (e.g., sand) refers to the particle size smaller than 4.75 mm but larger than 75 μm (i.e., not passing through a No. 200 sieve). In addition, blast-furnace slag — a by-product of the iron industry usually obtained by crushing blast furnace slag — is also used sometimes as coarse aggregate [Mehta 1986].

2.2.2 Cement

The binding material used to make concrete is formed from a pulverized material called *cement* and water. Cement by itself is not a binder; rather, it develops adhesive and cohesive properties as result of *hydration*, a chemical reaction between the cement minerals and water. Accordingly, such cements are called *hydraulic* cements.

Properly proportioned and mixed, cement and water together form a paste with stable adhesive characteristics that bind the constituent aggregates. The most commonly used cement is *portland cement*, which consists mainly of calcium silicates. ASTM C 150 defines portland cement as a hydraulic cement produced by pulverizing clinkers consisting essentially of hydraulic calcium and aluminum silicates. The addition of water to these minerals results in a paste that achieves stone-like strength upon hardening.

Cements can be hydraulic or nonhydraulic. Hydraulic cements are characterized by their ability to harden by reacting with water, and also to form a water-resistant product. Products formed from nonhydraulic cements are not resistant to water. Cements formed from calcination of gypsum or carbonates, such as limestone, are nonhydraulic.

Cements are classified on the basis of their rate of strength development, heat of hydration (low, moderate, or high), and resistance to sulfates (moderate or high). ASTM C 150 recognizes eight types of portland cements (Types I, IA, II, IIA, III, IIIA, IV, and V) that are commercially available to suit various needs. In addition, ASTM C 595-95 lists several categories of blended hydraulic cements.

2.2.3 Admixtures

Admixtures are chemical agents that are added to constituents of concrete before or during the mixing of concrete. ASTM C 125 defines an admixture as a material other than water, aggregates, hydraulic cements, and fiber reinforcement, which is used as an ingredient of concrete mix and added to the batch immediately before or during mixing. The admixtures serve to modify the properties and performance of concrete to suit specific job requirements or for better economy. These include improved workability, increased strength, retarding or accelerating strength development, and increasing frost resistance. ASTM C 494-92 classifies admixtures as air-entraining admixtures, accelerating admixtures, water-reducing and set-controlling admixtures, admixtures for flowing concrete, and miscellaneous. ACI Committee 212 further classifies miscellaneous admixtures into 12 other types.

Conforming to ASTM C 260, *air-entraining admixtures* are used to increase resistance of concrete to freezing and thawing and provide better resistance to the deteriorating action of de-icing salts. The overall purpose is to increase concrete's durability. Accelerating admixtures are used to increase the rate of early strength development of concrete. They are also used — particularly in cold weather — to expedite the start of finishing operation and reduce the time required for curing and protection. Retarding admixtures are used to permit placement and finishing; to overcome damaging and accelerating effects of high temperatures; and to control setting time of large structural units to keep the concrete workable through the entire placing period [ACI Com. 212].

2.3 TYPES OF CONCRETE

Concrete is generally classified in two ways: by unit weight and by compressive strength.

2.3.1 Classification Based on Unit Weight

Based on unit weight, concrete is classified into three types:

1. *Normal weight concrete*: This weighs about 145 to 155 lb/ft^3 (145 lb/ft^3 is commonly used for calculating the modulus of elasticity of normal weight concrete, E_c, according to the ACI Code) and uses a maximum aggregate size of 3/4 in. This is the most commonly used type of concrete for structural applications.
2. *Lightweight concrete*: The unit weight of structural lightweight concrete varies between 90 and 120 lb/ft^3 (about 3000 lb/yd^3). ACI 318-99 defines structural lightweight concrete as "concrete containing lightweight aggregate that conforms to Section 3.3.1 of ACI 318-02 and has air-dry unit weight as determined by 'Test Method for Unit Weight of Structural Lightweight Concrete'" (ASTM C 567), not exceeding 115 lb/ft^3. Lightweight aggregate is defined as aggregate with a dry loose weight of 70 lb/ft^3.
3. *Heavyweight concrete*: Produced from high-density aggregates, the heavyweight concrete weighs between 200 and 270 lb/ft^3. It is a special-purpose concrete, used at times for radiation shielding in nuclear power plants when limitation of usable space requires a reduction in the thickness of the shield.

2.3.2 Classification Based on Strength

This classification is based on the 28-day compressive strength of concrete (f_c') [Mehta 1986]:

1. Low-strength concrete (f_c' less than 3000 psi)
2. Medium-strength concrete (f_c' between 3000 and 6000 psi)
3. High-strength concrete (f_c' between 6000 and 10,000 psi)
4. Ultra high-strength concrete (f_c' above 10,000 psi)

For common construction purposes, such as buildings and bridges, normal weight concrete in the strength range of 3000 to 4000 psi is usually used. For prestressed concrete, concrete in the strength range of 5000 to 6000 psi is used. Use of concrete over 6000 psi strength (high-strength concrete) is not very common. Use of high-strength concrete usually requires a special permit from jurisdictional building officials to ensure quality control and the production of concrete of consistent strength.

2.4 STRENGTH OF CONCRETE

As a building material, concrete is strong in compression but weak in tension. To overcome this deficiency, the tensile zone of a concrete member is reinforced with steel or *fiber reinforced polymer* (FRP) reinforcing bars. The compressive strength of concrete is the most important design parameter in reinforced concrete design. Other strength parameters — such as tensile strength, shear strength, bearing strength, and modulus of rupture — are assumed as some fractions of the compressive strength [ACI 318-02].

The compressive strength of concrete, determined through a standard ASTM procedure, depends on several factors as follows:

1. Proportions of ingredients including aggregate quality
2. Effect of specimen size
3. Water-cement ratio
4. Type of vibration (i.e., low to high degree of compaction)
5. Type of curing
6. Rate of loading
7. Age-strength relationship

Two batches of concrete produced under identical conditions can vary widely in their properties.

With the onset of *curing of concrete** mixture, the compressive strength rapidly increases with age up to a certain time, after which the increase in strength is not much. The age-strength relationship for various curing periods and under various humidity conditions is shown in Figure 2.1 [Kosmatka and Panarese 1992]. The

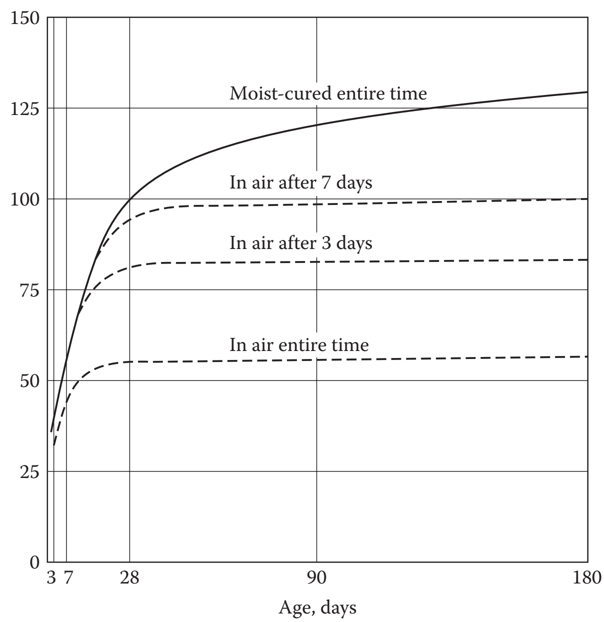

FIGURE 2.1 Age-strength relationships for the curing period of concrete. (Modified from Kosmatka, S.H. and Panarese, W.C., *Design and Control of Concrete Mixtures*, 13th ed, Chicago: Portland Cement Association, 1992. With permission.)

* The term "curing of concrete" refers to procedures devoted to promote cement hydration, such as control of time, temperature, and humidity conditions immediately after the placement of a concrete mixture into formwork.