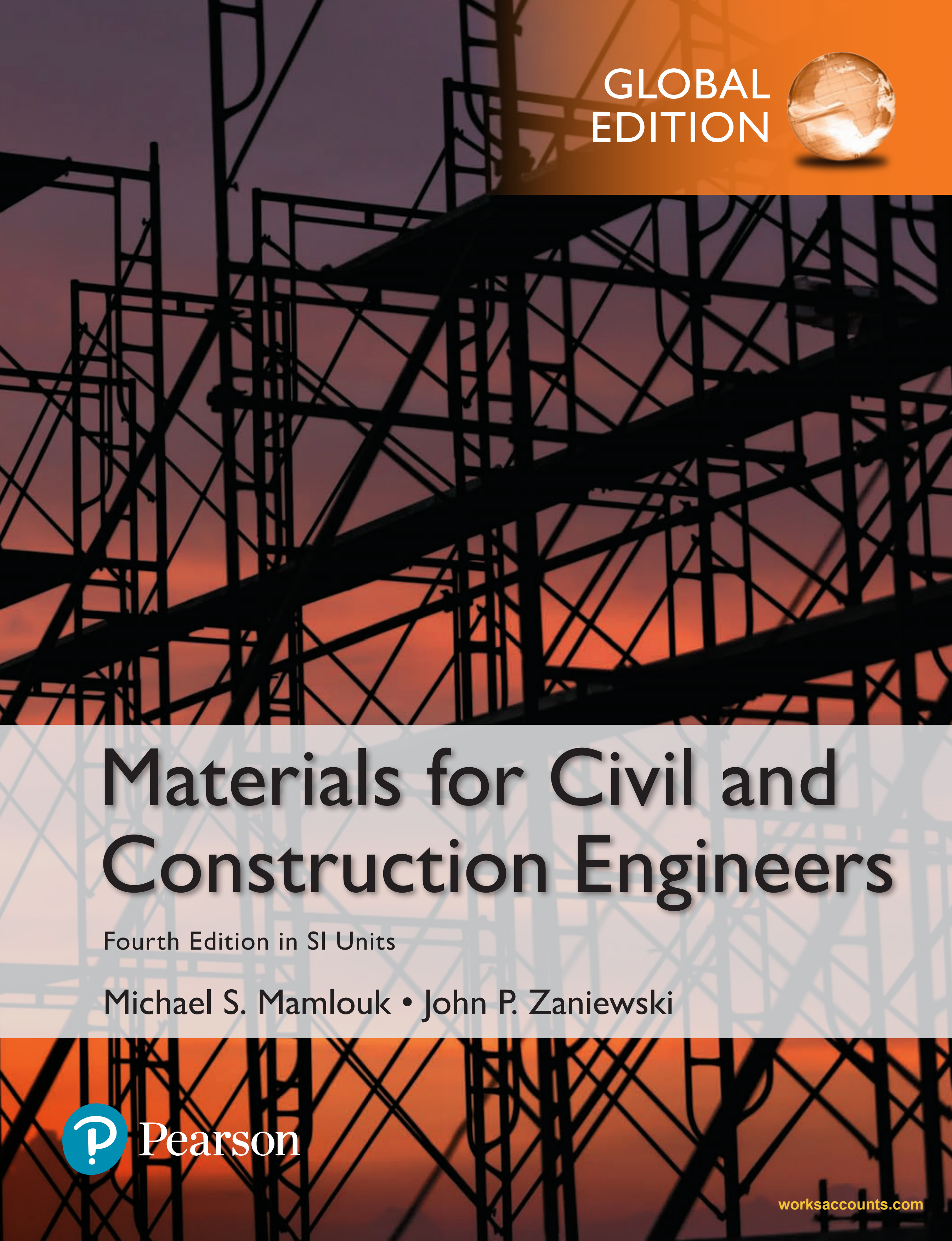

GLOBAL EDITION

Materials for Civil and Construction Engineers

Fourth Edition in SI Units

Michael S. Mamlouk • John P. Zaniewski

Pearson

MATERIALS FOR CIVIL AND CONSTRUCTION ENGINEERS

FOURTH EDITION IN SI UNITS

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PREFACE

A basic function of civil and construction engineering is to provide and maintain the infrastructure needs of society. The infrastructure includes buildings, water treatment and distribution systems, waste water removal and processing, dams, and highway and airport bridges and pavements. Although some civil and construction engineers are involved in the planning process, most are concerned with the design, construction, and maintenance of facilities. The common denominator among these responsibilities is the need to understand the behavior and performance of materials. Although not all civil and construction engineers need to be material specialists, a basic understanding of the material selection process, and the behavior of materials, is a fundamental requirement for all civil and construction engineers performing design, construction, and maintenance.

Material requirements in civil engineering and construction facilities are different from material requirements in other engineering disciplines. Frequently, civil engineering structures require tons of materials with relatively low replications of specific designs. Generally, the materials used in civil engineering have relatively low unit costs. In many cases, civil engineering structures are formed or fabricated in the field under adverse conditions. Finally, many civil engineering structures are directly exposed to detrimental effects of the environment.

The subject of engineering materials has advanced greatly in the past few decades. As a result, many of the conventional materials have either been replaced by more efficient materials or modified to improve their performance. Civil and construction engineers have to be aware of these advances and be able to select the most cost-effective material or use the appropriate modifier for the specific application at hand.

This text is organized into three parts: (1) introduction to materials engineering, (2) characteristics of materials used in civil and construction engineering, and (3) laboratory methods for the evaluation of materials.

The introduction to materials engineering includes information on the basic mechanistic properties of materials, environmental influences, and basic material classes. In addition, one of the responsibilities of civil and construction engineers is the inspection and quality control of materials in the construction process. This requires an understanding of material variability and testing procedures. The atomic structure of materials is covered in order to provide basic understanding of material behavior and to relate the molecular structure to the engineering response.

The second section, which represents a large portion of the book, presents the characteristics of the primary material types used in civil and construction engineering: steel, aluminum, concrete, masonry, asphalt, wood, and composites. Since the discussion of concrete and asphalt materials requires a basic knowledge of aggregates, there is a chapter on aggregates. Moreover, since composites are gaining wide acceptance among engineers and are replacing many of the conventional materials, there is a chapter introducing composites.

The discussion of each type of material includes information on the following:

- Basic structure of the materials
- Material production process
- Mechanistic behavior of the material and other properties
- Environmental influences
- Construction considerations
- Special topics related to the material discussed in each chapter

Finally, each chapter includes an overview of various test procedures to introduce the test methods used with each material. However, the detailed description of the test procedures is left to the appropriate standards organizations such as the American Society for Testing and Materials (ASTM) and the American Association of State Highway and Transportation Officials (AASHTO). These ASTM and AASHTO standards are usually available in college libraries, and students are encouraged to use them. Also, there are sample problems in most chapters, as well as selected questions and problems at the end of each chapter. Answering these questions and problems will lead to a better understanding of the subject matter.

There are volumes of information available for each of these materials. It is not possible, or desirable, to cover these materials exhaustively in an introductory single text. Instead, this book limits the information to an introductory level, concentrates on current practices, and extracts information that is relevant to the general education of civil and construction engineers.

The content of the book is intended to be covered in one academic semester, although quarter system courses can definitely use it. The instructor of the course can also change the emphasis of some topics to match the specific curriculum of the department. Furthermore, since the course usually includes a laboratory portion, a number of laboratory test methods are described. The number of laboratory tests in the book is more than what is needed in a typical semester in order to provide more flexibility to the instructor to use the available equipment. Laboratory tests should be coordinated with the topics covered in the lectures so that the students get the most benefit from the laboratory experience.

The first edition of this textbook served the needs of many universities and colleges. Therefore, the second edition was more of a refinement and updating of the book, with some notable additions. Several edits were made to the steel chapter to improve the description of heat treatments, phase diagram, and the heat-treating effects of welding. Also, a section on stainless steel was added, and current information on the structural uses of steel was provided. The cement and concrete chapters have been augmented with sections on hydration-control admixtures, recycled wash water, silica fume, self-consolidating concrete, and flowable fill. When the first edition was published, the Superpave mix design method was just being introduced to the industry. Now Superpave is a well-established method that has been field tested and revised to better meet the needs of the paving community. This development required a complete revision to the asphalt chapter to accommodate the current methods and procedures for both Performance Grading of asphalt binders and the Superpave mix design method. The chapter on wood was revised to provide information on recent manufactured wood products that became available in the past several years. Also, since fiber-reinforced polymer composites have been more commonly used in retrofitting old and partially damaged structures, several examples were added in the chapter on composites. In the laboratory manual, an experiment on dry-rodded unit weight of aggregate that is used in portland cement concrete (PCC) proportioning was added, and the experiment on creep of asphalt concrete was deleted for lack of use.

What's New in This Edition

The primary focus of the updates presented in this edition was on the sustainability of materials used in civil and construction engineering. The information on sustainability in Chapter 1 was updated and expanded to include recent information on sustainability. In addition, a section was added to Chapters 3 through 11 describing the sustainability considerations of each material. The problem set for each chapter was updated and increased to provide some fresh Exercises and to cover other topics discussed in the chapter. References were updated and increased in all chapters to provide students with additional reading on current issues related to different materials. Many figures were added and others were updated throughout the book to provide visual illustrations to students. Other specific updates to the chapters include:

- Chapter 1 now includes a more detailed section on viscoelastic material behavior and a new sample problem.
- Chapter 3 was updated with recent information about the production of steel.
- A sample problem was added to Chapter 5 about the water absorbed by aggregate in order to highlight the fact that absorbed water is not used to hydrate the cement or improve the workability of plastic concrete.
- Two new sample problems were added to Chapter 6 on the acceptable criteria of mixing water and to clarify the effect of water reducer on the properties of concrete.
- Chapter 7 was augmented with a discussion of concrete mixing water and a new sample problem. A section on pervious concrete was added to reflect the current practice on some parking lots and pedestrian walkways.
- Chapter 9 was updated with reference to the multiple stress creep recovery test, and the information about the immersion compression test was replaced with the tensile strength ratio method to reflect current practices. The selection of the binder was refined to incorporate the effect of load and speed. The section on the diameteral tensile resilient modulus was removed for lack of use. The sample problem on the diameteral tensile resilient modulus was also removed and replaced with a sample problem on the freeze-thaw test and the tensile strength ratio.

- Chapter 10 was updated to include more information about wood deterioration and preservation. The first two sample problems were edited to provide more accurate solutions since the shrinkage values used in wood are related to the green dimensions at or above the fiber saturation point (FSP), not the dry dimensions. The third sample problem was expanded to demonstrate how to determine the modulus of elasticity using the third-point bending test.
- Chapter 11 was updated to reflect information about the effective length of fibers and the ductility of fiber-reinforced polymers (FRP). The discussion was expanded with several new figures to incorporate fibers, fabrics, laminates, and composites used in civil engineering applications. The first sample problem was expanded to apply other concepts covered in the chapter.
- The laboratory manual in the appendix was updated to include two new experiments on creep in polymers and the effect of fiber orientation on the elastic modulus of fiber reinforced composites. The experiment on the tensile properties of composites was updated. This would allow more options to the instructor to choose from in assigning lab experiments to students.

Acknowledgments

The authors would like to acknowledge the contributions of many people who assisted with the development of this new edition. First, the authors wish to thank the reviewers and recognize the fact that most of their suggestions have been incorporated into the fourth edition, in particular Dr. Dimitrios Goulias of University of Maryland, Tyler Witthuhn of the National Concrete Masonry Association, Mr. Philip Line of American Wood Council, Dr. Baoshan Huang of University of Tennessee, and Dr. Steve Krause of Arizona State University. Appreciation is also extended to Drs. Narayanan Neithalath, Shane Underwood, Barzin Mobasher, and Kamil Kaloush of Arizona State University for their valuable technical contributions. The photos of FRP materials contributed by Dr. Hota GangaRao of the Constructed Facilities Center at West Virginia University are appreciated. Appreciation also goes to Dr. Javed Bari, formerly with the Arizona Department of Transportation for his contribution in preparing the slides and to Dr. Mena Souliman of the University of Texas at Tyler for his contribution in the preparation of the solution manual.

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CHAPTER 1

MATERIALS ENGINEERING CONCEPTS

Materials engineers are responsible for the selection, specification, and quality control of materials to be used in a job. These materials must meet certain classes of criteria or materials properties (Ashby and Jones, 2011). These classes of criteria include

- economic factors
- mechanical properties
- nonmechanical properties
- production/construction considerations
- aesthetic properties

In addition to this traditional list of criteria, civil engineers must be concerned with environmental quality. In 1997, the ASCE *Code of Ethics* was modified to include "sustainable development" as an ethics issue. Sustainable development basically recognizes the fact that our designs should be sensitive to the ability of future generations to meet their needs. There is a strong tie between the materials selected for design and sustainable development.

When engineers select the material for a specific application, they must consider the various criteria and make compromises. Both the client and the purpose of the facility or structure dictate, to a certain extent, the emphasis that will be placed on the different criteria.

Civil and construction engineers must be familiar with materials used in the construction of a wide range of structures. Materials most frequently used include steel, aggregate, concrete, masonry, asphalt, and wood. Materials used to a lesser extent include aluminum, glass, plastics, and fiber-reinforced composites. Geotechnical engineers make a reasonable case for including soil as the most widely used engineering material, since it provides the basic support for all civil engineering structures. However, the properties of soils will not be discussed in this text because soil properties are generally the topic of a separate course in civil and construction engineering curriculums.

Recent advances in the technology of civil engineering materials have resulted in the development of better quality, more economical, and safer materials. These materials are commonly referred to as high-performance materials. Because more is known about the molecular structure of materials and because of the continuous research efforts by scientists and engineers, new materials such as polymers, adhesives, composites, geotextiles, coatings, cold-formed metals, and various synthetic products are competing with traditional civil engineering materials. In addition, improvements have been made to existing materials by changing their molecular structures or including additives to improve quality, economy, and performance. For example, superplasticizers have made a breakthrough in the concrete industry, allowing the production of much stronger concrete. Joints made of elastomeric materials have improved the safety of high-rise structures in earthquake-active areas. Lightweight synthetic aggregates have decreased the weight of concrete structures, allowing small cross-sectional areas of components. Polymers have been mixed with asphalt, allowing pavements to last longer under the effect of vehicle loads and environmental conditions.

The field of fiber composite materials has developed rapidly in the past 30 years. Many recent civil engineering projects have used fiber-reinforced polymer composites. These advanced composites compete with traditional materials due to their higher strength-to-weight ratio and their ability to overcome such shortcomings as corrosion. For example, fiber-reinforced concrete has much greater toughness than conventional portland cement concrete. Composites can replace reinforcing steel in concrete structures. In fact, composites have allowed the construction of structures that could not have been built in the past.

The nature and behavior of civil engineering materials are as complicated as those of materials used in any other field of engineering. Due to the high quantity of materials used in civil engineering projects, the civil engineer frequently works with locally available materials that are not as highly refined as the materials used in other engineering fields. As a result, civil engineering materials frequently have highly variable properties and characteristics.

This chapter reviews the manner in which the properties of materials affect their selection and performance in civil engineering applications. In addition, this chapter reviews some basic definitions and concepts of engineering mechanics required for understanding material behavior. The variable nature of material properties is also discussed so that the engineer will understand the concepts of precision and accuracy, sampling, quality assurance, and quality control. Finally, instruments used for measuring material response are described.

1.1 Economic Factors

The economics of the material selection process are affected by much more than just the cost of the material. Factors that should be considered in the selection of the material include

- availability and cost of raw materials
- manufacturing costs

- transportation
- placing
- maintenance

The materials used for civil engineering structures have changed over time. Early structures were constructed of stone and wood. These materials were in ready supply and could be cut and shaped with available tools. Later, cast iron was used, because mills were capable of crudely refining iron ore. As the industrial revolution took hold, quality steel could be produced in the quantities required for large structures. In addition, portland cement, developed in the mid-1800s, provided civil engineers with a durable inexpensive material with broad applications.

Due to the efficient transportation system in the United States, availability is not as much of an issue as it once was in the selection of a material. However, transportation can significantly add to the cost of the materials at the job site. For example, in many locations in the United States, quality aggregates for concrete and asphalt are in short supply. The closest aggregate source to Houston, Texas, is 150 km from the city. This haul distance approximately doubles the cost of the aggregates in the city, and hence puts concrete at a disadvantage compared with steel.

The type of material selected for a job can greatly affect the ease of construction and the construction costs and time. For example, the structural members of a steel-frame building can be fabricated in a shop, transported to the job site, lifted into place with a crane, and bolted or welded together. In contrast, for a reinforced concrete building, the forms must be built; reinforcing steel placed; concrete mixed, placed, and allowed to cure; and the forms removed. Constructing the concrete frame building can be more complicated and time consuming than constructing steel structures. To overcome this shortcoming, precast concrete units commonly have been used, especially for bridge construction.

All materials deteriorate over time and with use. This deterioration affects both the maintenance cost and the useful life of the structure. The rate of deterioration varies among materials. Thus, in analyzing the economic selection of a material, the life cycle cost should be evaluated in addition to the initial costs of the structure.

1.2 Mechanical Properties

The mechanical behavior of materials is the response of the material to external loads. All materials deform in response to loads; however, the specific response of a material depends on its properties, the magnitude and type of load, and the geometry of the element. Whether the material "fails" under the load conditions depends on the failure criterion. Catastrophic failure of a structural member, resulting in the collapse of the structure, is an obvious material failure. However, in some cases, the failure is more subtle, but with equally severe consequences. For example, pavement may fail due to excessive roughness at the surface, even though the stress levels are well within the capabilities of the material. A building may have to be closed due to excessive vibrations by wind or other live loads, although it could be structurally sound. These are examples of *functional* failures.

1.2.1 Loading Conditions

One of the considerations in the design of a project is the type of loading that the structure will be subjected to during its design life. The two basic types of loads are static and dynamic. Each type affects the material differently, and frequently the interactions between the load types are important. Civil engineers encounter both when designing a structure.

Static loading implies a sustained loading of the structure over a period of time. Generally, static loads are slowly applied such that no shock or vibration is generated in the structure. Once applied, the static load may remain in place or be removed slowly. Loads that remain in place for an extended period of time are called *sustained* (dead) loads. In civil engineering, much of the load the materials must carry is due to the weight of the structure and equipment in the structure.

Loads that generate a shock or vibration in the structure are *dynamic* loads. Dynamic loads can be classified as *periodic, random,* or *transient,* as shown in Figure 1.1 (Richart et al., 1970). A periodic load, such as a harmonic or sinusoidal load, repeats itself with time. For example, rotating equipment in a building can produce a vibratory load. In a random load, the load pattern never repeats, such as that produced by earthquakes. Transient load, on the other hand, is an impulse load that is applied over a short time interval, after which the vibrations decay until the

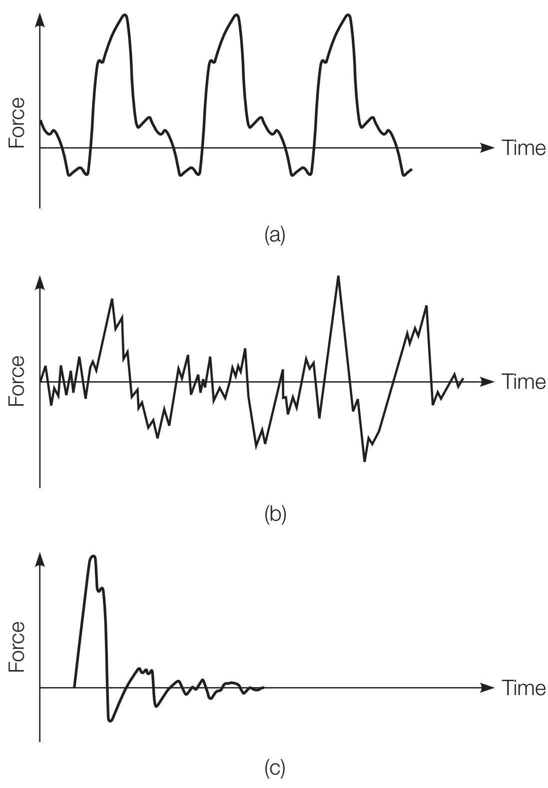

FIGURE 1.1 Types of dynamic loads: (a) periodic, (b) random, and (c) transient.

system returns to a rest condition. For example, bridges must be designed to withstand the transient loads of trucks.

1.2.2 Stress–Strain Relations

Materials deform in response to loads or forces. In 1678, Robert Hooke published the first findings that documented a linear relationship between the amount of force applied to a member and its deformation. The amount of deformation is proportional to the properties of the material and its dimensions. The effect of the dimensions can be normalized. Dividing the force by the cross-sectional area of the specimen normalizes the effect of the loaded area. The force per unit area is defined as the stress σ in the specimen (i.e., σ = force/area). Dividing the deformation by the original length is defined as strain ε of the specimen (i.e., ε = change in length/original length). Much useful information about the material can be determined by plotting the stress–strain diagram.

Figure 1.2 shows typical uniaxial tensile or compressive stress–strain curves for several engineering materials. Figure 1.2(a) shows a linear stress–strain relationship up to the point where the material fails. Glass and chalk are typical of materials exhibiting this tensile behavior. Figure 1.2(b) shows the behavior of steel in tension. Here, a linear relationship is obtained up to a certain point (proportional limit), after which the material deforms without much increase in stress. On the other hand, aluminum alloys in tension exhibit a linear stress–strain relationship up to the proportional limit, after which a nonlinear relation follows, as illustrated in Figure 1.2(c). Figure 1.2(d) shows a nonlinear relation throughout the whole range. Concrete and other materials exhibit this relationship, although the first portion of the curve for concrete is very close to being linear. Soft rubber in tension differs from most materials in such a way that it shows an almost linear stress–strain relationship followed by a reverse curve, as shown in Figure 1.2(e).

1.2.3 Elastic Behavior

If a material exhibits true elastic behavior, it must have an instantaneous response (deformation) to load, and the material must return to its original shape when the load is removed. Many materials, including most metals, exhibit elastic behavior, at

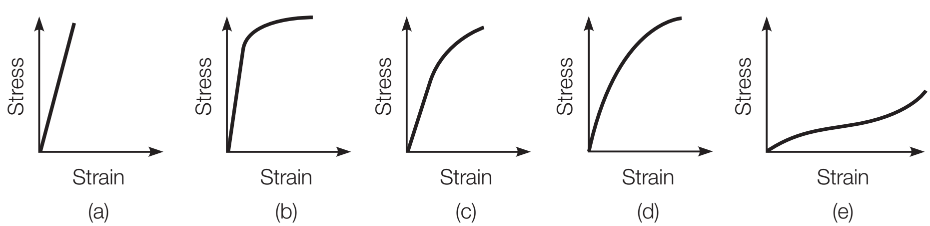

FIGURE 1.2 Typical uniaxial stress–strain diagrams for some engineering materials: (a) glass and chalk, (b) steel, (c) aluminum alloys, (d) concrete, and (e) soft rubber.

least at low stress levels. As will be discussed in Chapter 2, elastic deformation does not change the arrangement of atoms within the material, but rather it stretches the bonds between atoms. When the load is removed, the atomic bonds return to their original position.

Young observed that different elastic materials have different proportional constants between stress and strain. For a homogeneous, isotropic, and linear elastic material, the proportional constant between normal stress and normal strain of an axially loaded member is the *modulus of elasticity* or *Young's modulus, E,* and is equal to

$$E = \frac{\sigma}{\varepsilon} \tag{1.1}$$

where σ is the normal stress and ε is the normal strain.

In the axial tension test, as the material is elongated, there is a reduction of the cross section in the lateral direction. In the axial compression test, the opposite is true. The ratio of the lateral strain, ε_l, to the axial strain, ε_a, is *Poisson's ratio,*

$$v = \frac{-\varepsilon_l}{\varepsilon_a} \tag{1.2}$$

Since the axial and lateral strains will always have different signs, the negative sign is used in Equation 1.2 to make the ratio positive. Poisson's ratio has a theoretical range of 0.0 to 0.5, where 0.0 is for a compressible material in which the axial and lateral directions are not affected by each other. The 0.5 value is for a material that does not change its volume when the load is applied. Most solids have Poisson's ratios between 0.10 and 0.45.

Although Young's modulus and Poisson's ratio were defined for the uniaxial stress condition, they are important when describing the three-dimensional stress–strain relationships, as well. If a homogeneous, isotropic cubical element with linear elastic response is subjected to normal stresses σ_x, σ_y, and σ_z in the three orthogonal directions (as shown in Figure 1.3), the normal strains ε_x, ε_y, and ε_z can be computed by the *generalized Hooke's law,*

$$\varepsilon_x = \frac{\sigma_x - v(\sigma_y + \sigma_z)}{E}$$

$$\varepsilon_y = \frac{\sigma_y - v(\sigma_z + \sigma_x)}{E}$$

$$\varepsilon_z = \frac{\sigma_z - v(\sigma_x + \sigma_y)}{E} \tag{1.3}$$

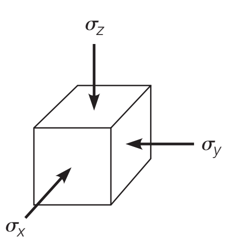

FIGURE 1.3 Normal stresses applied on a cubical element.

Sample Problem 1.1

A cube made of an alloy with dimensions of 50 mm × 50 mm × 50 mm is placed into a pressure chamber and subjected to a pressure of 90 MPa. If the modulus of elasticity of the alloy is 100 GPa and Poisson's ratio is 0.28, what will be the length of each side of the cube, assuming that the material remains within the elastic region?

Solution

$$\begin{aligned}
\varepsilon_x &= [\sigma_x - \nu(\sigma_y + \sigma_z)]/E = [-90 - 0.28 \times (-90 - 90)]/100000 \\
&= -0.000396 \text{ m/m} \\
\varepsilon_y &= \varepsilon_z = -0.000396 \text{ m/m} \\
\Delta x &= \Delta y = \Delta z = -0.000396 \times 50 = -0.0198 \text{ mm} \\
L_{\text{new}} &= 50 - 0.0198 = 49.9802 \text{ mm}
\end{aligned}$$

Linearity and elasticity should not be confused. A *linear material*'s stress–strain relationship follows a straight line. An *elastic material* returns to its original shape when the load is removed and reacts instantaneously to changes in load. For example, Figure 1.4(a) represents a linear elastic behavior, while Figure 1.4(b) represents a nonlinear elastic behavior.

For materials that do not display any linear behavior, such as concrete and soils, determining a Young's modulus or elastic modulus can be problematical. There are several options for arbitrarily defining the modulus for these materials. Figure 1.5 shows four options: the initial tangent, tangent, secant, and chord moduli. The *initial tangent modulus* is the slope of the tangent of the stress–strain curve at the origin. The *tangent modulus* is the slope of the tangent at a point on the stress–strain curve. The *secant modulus* is the slope of a chord drawn between the origin and an arbitrary point on the stress–strain curve. The *chord modulus* is the slope of a chord drawn between two points on the stress–strain curve. The selection of which modulus to use for a nonlinear material depends on the stress or strain level at which the material typically is used. Also, when determining the tangent, secant, or chord modulus, the stress or strain levels must be defined.

Table 1.1 shows typical modulus and Poisson's ratio values for some materials at room temperature. Note that some materials have a range of modulus values rather

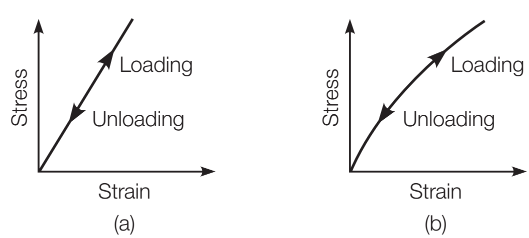

FIGURE 1.4 Elastic behavior: (a) linear and (b) nonlinear.

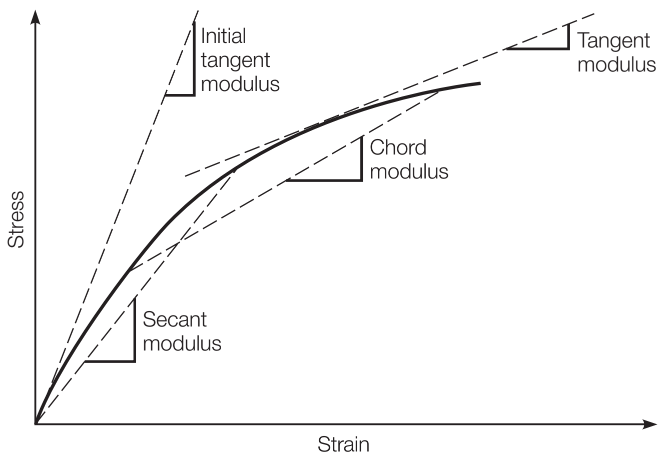

FIGURE 1.5 Methods for approximating modulus.

than a distinct value. Several factors affect the modulus, such as curing level and proportions of components of concrete or the direction of loading relative to the grain of wood.

1.2.4 Elastoplastic Behavior

For some materials, as the stress applied on the specimen is increased, the strain will proportionally increase up to a point; after this point, the strain will increase with little additional stress. In this case, the material exhibits linear elastic behavior

TABLE 1.1 Typical Modulus and Poisson's Ratio Values (Room Temperature)

Material	Modulus GPa	Poisson's Ratio
Aluminum	69–75	0.33
Brick	10–17	0.23–0.40
Cast iron	75–169	0.17
Concrete	14–40	0.11–0.21
Copper	110	0.35
Epoxy	3–140	0.35–0.43
Glass	62–70	0.25
Limestone	58	0.2–0.3
Rubber (soft)	0.001–0.014	0.49
Steel	200	0.27
Tungsten	407	0.28
Wood	6–15	0.29–0.45

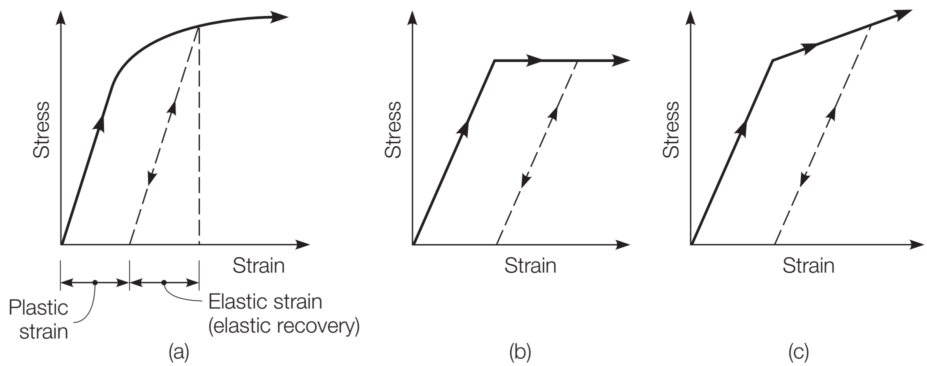

FIGURE 1.6 Stress–strain behavior of plastic materials: (a) example of loading and unloading, (b) elastic–perfectly plastic, and (c) elasto–plastic with strain hardening.

followed by plastic response. The stress level at which the behavior changes from elastic to plastic is the *elastic limit.* When the load is removed from the specimen, some of the deformation will be recovered and some of the deformation will remain as seen in Figure 1.6(a). As discussed in Chapter 2, plastic behavior indicates permanent deformation of the specimen so that it does not return to its original shape when the load is removed. This indicates that when the load is applied, the atomic bonds stretch, creating an elastic response; then the atoms actually slip relative to each other. When the load is removed, the atomic slip does not recover; only the atomic stretch is recovered (Callister, 2006).

Several models are used to represent the behavior of materials that exhibit both elastic and plastic responses. Figure 1.6(b) shows a linear elastic–perfectly plastic response in which the material exhibits a linear elastic response upon loading, followed by a completely plastic response. If such material is unloaded after it has plasticly deformed, it will rebound in a linear elastic manner and will follow a straight line parallel to the elastic portion, while some permanent deformation will remain. If the material is loaded again, it will have a linear elastic response followed by plastic response at the same level of stress at which the material was unloaded (Popov, 1968).

Figure 1.6(c) shows an elastoplastic response in which the first portion is an elastic response followed by a combined elastic and plastic response. If the load is removed after the plastic deformation, the stress–strain relationship will follow a straight line parallel to the elastic portion; consequently, some of the strain in the material will be removed, and the remainder of the strain will be permanent. Upon reloading, the material again behaves in a linear elastic manner up to the stress level that was attained in the previous stress cycle. After that point the material will follow the original stress–strain curve. Thus, the stress required to cause plastic deformation actually increases. This process is called *strain hardening* or *work hardening.* Strain hardening is beneficial in some cases, since it allows more stress to be applied without permanent deformation. In the production of cold-formed steel framing members, the permanent deformation used in the production process can double the yield strength of the member relative to the original strength of the steel.

Some materials exhibit *strain softening,* in which plastic deformation causes weakening of the material. Portland cement concrete is a good example of such a material. In this case, plastic deformation causes microcracks at the interface between aggregate and cement paste.

Sample Problem 1.2

An elastoplastic material with strain hardening has the stress–strain relationship shown in Figure 1.6(c). The modulus of elasticity is 175 GPa, yield strength is 480 MPa, and the slope of the strain-hardening portion of the stress–strain diagram is 20.7 GPa.

a. Calculate the strain that corresponds to a stress of 550 MPa.
b. If the 550-MPa stress is removed, calculate the permanent strain.

Solution

(a) $\varepsilon = (480/175 \times 10^3) + [(550 - 480)/20.7 \times 10^3] = 0.0061 \text{ m/m}$

(b) $\varepsilon_{\text{permanent}} = 0.0061 - [550/(175 \times 10^3)] = 0.0061 - 0.0031$

$= 0.0030 \text{ m/m}$

Materials that do not undergo plastic deformation prior to failure, such as concrete, are said to be *brittle,* whereas materials that display appreciable plastic deformation, such as mild steel, are *ductile.* Generally, ductile materials are preferred for construction. When a brittle material fails, the structure can collapse in a catastrophic manner. On the other hand, overloading a ductile material will result in distortions of the structure, but the structure will not necessarily collapse. Thus, the ductile material provides the designer with a margin of safety.

Figure 1.7(a) demonstrates three concepts of the stress–strain behavior of elastoplastic materials. The lowest point shown on the diagram is the *proportional limit,* defined as the transition point between linear and nonlinear behavior. The second point is the *elastic limit,* which is the transition between elastic and plastic behavior. However, most materials do not display an abrupt change in behavior from elastic to plastic. Rather, there is a gradual, almost imperceptible transition between the behaviors, making it difficult to locate an exact transition point (Polowski and Ripling, 2005). For this reason, arbitrary methods such as the *offset* and the *extension* methods, are used to identify the elastic limit, thereby defining the *yield stress (yield strength).* In the offset method, a specified offset is measured on the abscissa, and a line with a slope equal to the initial tangent modulus is drawn through this

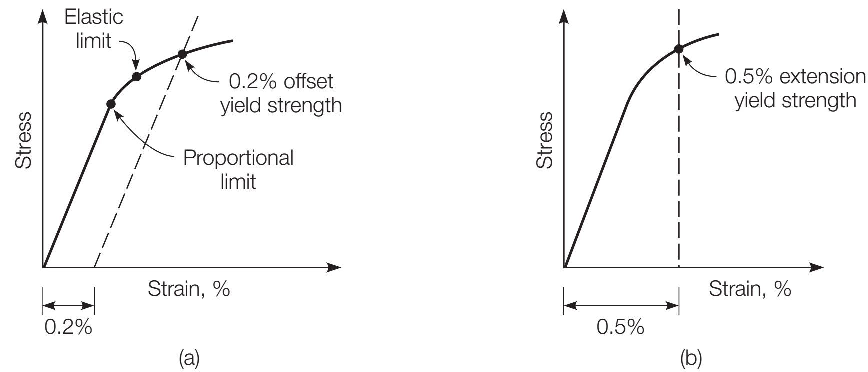

FIGURE 1.7 Methods for estimating yield stress: (a) offset method and (b) extension method.

point. The point where this line intersects the stress–strain curve is the *offset yield stress* of the material, as seen in Figure 1.7(a). Different offsets are used for different materials (Table 1.2). The *extension yield stress* is located where a vertical projection, at a specified strain level, intersects the stress–strain curve. Figure 1.7(b) shows the yield stress corresponding to 0.5% extension.

Sample Problem 1.3

A rod made of aluminum alloy, with a gauge length of 100 mm, diameter of 10 mm, and yield strength of 150 MPa, was subjected to a tensile load of 5.85 kN. If the gauge length was changed to 100.1 mm and the diameter was changed to 9.9967 mm, calculate the modulus of elasticity and Poisson's ratio.

Solution

$$\sigma = P/A = (5850 \text{ N})/[\pi(5 \times 10^{-3} \text{ m})^2] = 74.5 \times 10^6 \text{ Pa} = 74.5 \text{ MPa}$$

Since the applied stress is well below the yield strength, the material is within the elastic region.

$$\varepsilon_a = \Delta L/L = (100.1 - 100)/100 = 0.001$$
$$E = \sigma/\varepsilon_a = 74.5/0.001 = 74{,}500 \text{ MPa} = 74.5 \text{ GPa}$$
$$\varepsilon_l = \text{change in diameter/diameter} = (9.9967 - 10)/10 = -0.00033$$
$$\nu = -\varepsilon_l/\varepsilon_a = 0.00033/0.001 = 0.33$$

TABLE 1.2 Offset Values Typically Used to Determine Yield Stress

Material	Stress Condition	Offset (%)	Corresponding Strain
Steel	Tension	0.20	0.0020
Wood	Compression parallel to grain	0.05	0.0005
Gray cast iron	Tension	0.05	0.0005
Concrete	Compression	0.02	0.0002
Aluminum alloys	Tension	0.20	0.0020
Brass and bronze	Tension	0.35	0.0035

1.2.5 Viscoelastic Behavior

The previous discussion assumed that the strain was an immediate response to stress. This is an assumption for elastic and elastoplastic materials. However, no material has this property under all conditions. In some cases, materials exhibit both viscous and elastic responses, which are known as *viscoelastic.* Typical viscoelastic materials used in construction applications are asphalt and plastics.

Time-Dependent Response Viscoelastic materials have a delayed response to load application. For example, Figure 1.8(a) shows a sinusoidal axial load applied on a viscoelastic material, such as asphalt concrete, versus time. Figure 1.8(b) shows the

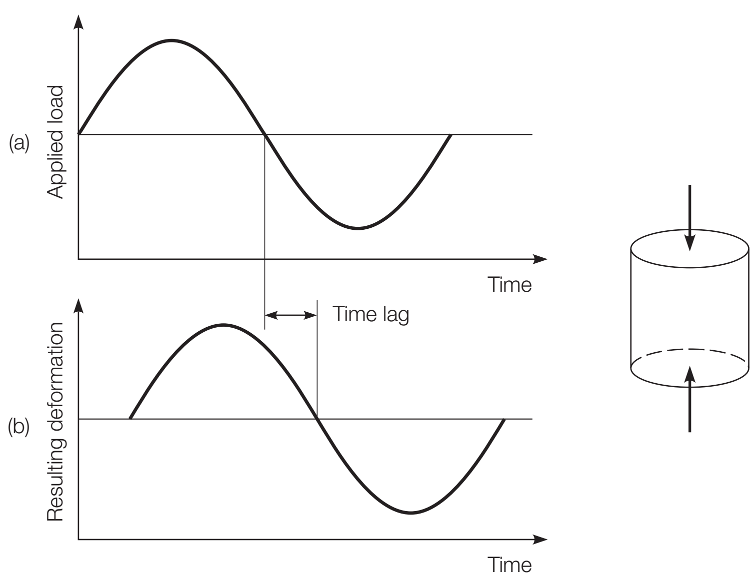

FIGURE 1.8 Load-deformation response of a viscoelastic material.

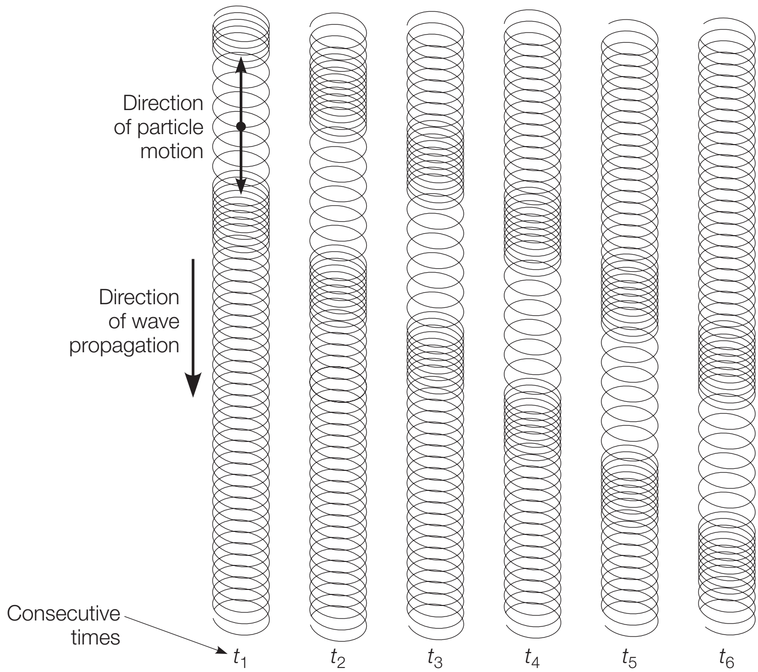

FIGURE 1.9 Delay of propagation of compression and dilation waves in a Slinky®.

resulting deformation versus time, where the deformation lags the load—that is, the maximum deformation of the sample occurs after the maximum load is applied. The amount of time delayed of the deformation depends on the material characteristics and the temperature.

The delay in the response of viscoelastic materials can be simulated by the movement of the Slinky® toy in the hand of a child, as illustrated in Figure 1.9. As the child moves her hand up and down, waves of compression and dilation are developed in the Slinky. However, the development of the waves in the Slinky does not happen exactly at the same time as the movements of the child's hand. For example, a compression wave could be propagating in one part of the Slinky at the same time when the child is moving her hand upward and *vice versa.* This occurs because of the delay in response relative to the action. Typical viscoelastic civil engineering materials, such as asphalt, have the same behavior, although they are not as flexible as a Slinky.

There are several mechanisms associated with time-dependent deformation, such as *creep* and *viscous flow.* There is no clear distinction between these terms. Creep is generally associated with long-term deformations and can occur in metals, ionic and covalent crystals, and amorphous materials. On the other hand, viscous flow is associated only with amorphous materials and can occur under short-term load duration. For example, concrete, a material with predominantly covalent crystals, can creep over a period of decades. Asphalt concrete pavements, an amorphous-binder material, can have ruts caused by the accumulated effect of viscous flows resulting from traffic loads with a load duration of only a fraction of a second.

Creep of metals is a concern at elevated temperatures. Steel can creep at temperatures greater than 30% of the melting point on the absolute scale. This can be a concern in the design of boilers and nuclear reactor containment vessels. Creep is also considered in the design of wood and advanced composite structural members. Wood elements loaded for a few days can carry higher stresses than elements designed to carry "permanent" loads. On the other hand, creep of concrete is associated with microcracking at the interface of the cement paste and the aggregate particles (Mehta and Monteiro, 2013).

The viscous flow models are similar in nature to Hooke's law. In linearly viscous materials, the rate of deformation is proportional to the stress level. These materials are not compressible and do not recover when the load is removed. Materials with these characteristics are *Newtonian fluids.*

Figure 1.10(a) shows a typical creep test in which a constant compressive stress is applied to an asphalt concrete specimen. In this case, an elastic strain will develop, followed by time-dependent strain or creep. If the specimen is unloaded, a part of the strain will recover instantaneously, while the remaining strain will recover, either completely or partially, over a period of time. Another phenomenon typical of time-dependent materials is relaxation, or dissipation of stresses with time. For example, if an asphalt concrete specimen is placed in a loading machine and subjected to a constant strain, the stress within the specimen will initially be high, then gradually dissipate due to relaxation as shown in Figure 1.10(b). Relaxation is an important concern in the selection of steel for a prestressed concrete design.

In viscoelasticity, there are two approaches used to describe how stresses, strains, and time are interrelated. One approach is to postulate mathematical

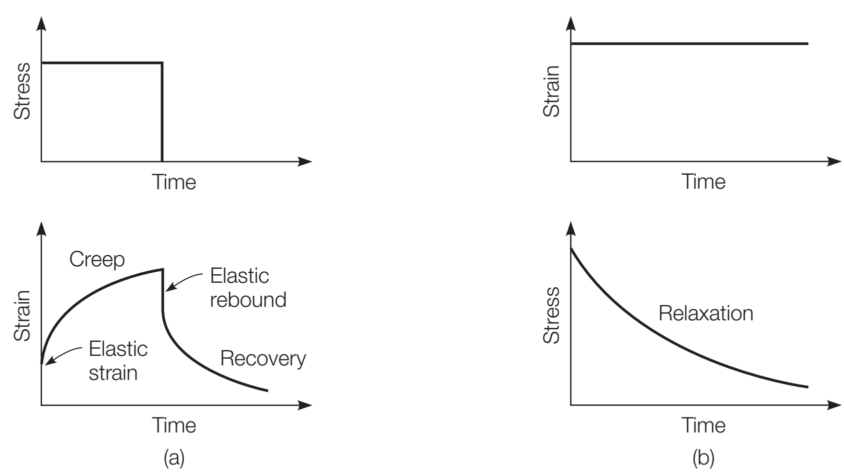

FIGURE 1.10 Behavior of time-dependent materials: (a) creep and (b) relaxation.

relations between these parameters based on material functions obtained from laboratory tests. The other approach is based on combining a number of discrete *rheological elements* to form *rheological models,* which describe the material response.

Rheological Models Rheological models are used to model mechanically the time-dependent behavior of materials. There are many different modes of material deformation, particularly in polymer materials. These materials cannot be described as simply elastic, viscous, etc. However, these materials can be modeled by a combination of simple physical elements. The simple physical elements have characteristics that can be easily visualized. Rheology uses three basic elements, combined in either series or parallel to form models that define complex material behaviors. The three basic rheological elements, Hookean, Newtonian, and St. Venant, are shown in Figure 1.11 (Polowski and Ripling, 2005).

The *Hookean* element, as in Figure 1.11(a), has the characteristics of a linear *spring.* The deformation δ is proportional to force F by a constant M:

$$F = M\delta \tag{1.4}$$

This represents a perfectly linear elastic material. The response to a force is instantaneous and the deformation is completely recovered when the force is removed. Thus, the Hookean element represents a perfectly linear elastic material.

A *Newtonian* element models a perfectly viscous material and is modeled as a *dashpot* or shock absorber as seen in Figure 1.11(b). The deformation for a given level of force is proportional to the amount of time the force is applied. Hence, the rate of deformation, for a constant force, is a constant β:

$$F = \beta\dot{\delta} \tag{1.5}$$

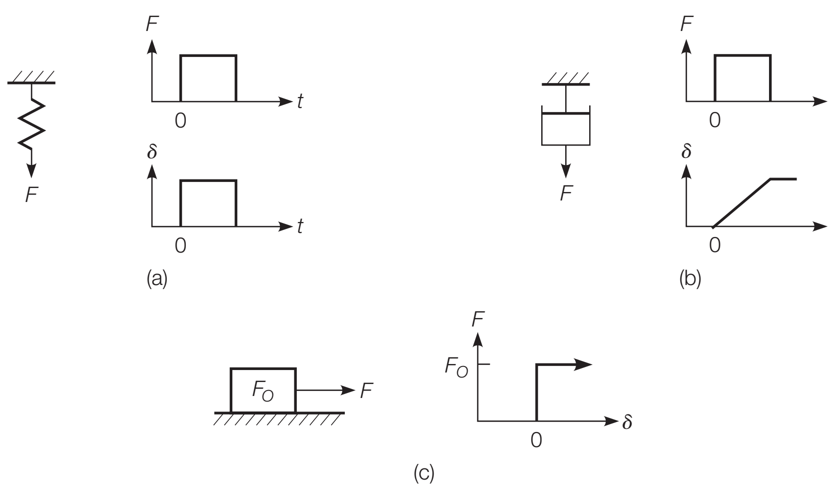

FIGURE 1.11 Basic elements used in rheology: (a) Hookean, (b) Newtonian, and (c) St. Venant.

The dot above the δ defines this as the rate of deformation with respect to time. If $\delta = 0$ at time $t = 0$ when a constant force F is applied, the deformation at time t is

$$\delta = \frac{Ft}{\beta} \tag{1.6}$$

When the force is removed, the specimen retains the deformed shape. There is no recovery of any of the deformation.

The *St. Venant* element, as seen in Figure 1.11(c), has the characteristics of a sliding block that resists movement by friction. When the force F applied to the element is less than the critical force F_O, there is no movement. If the force is increased to overcome the static friction, the element will slide and continue to slide as long as the force is applied. This element is unrealistic, since any sustained force sufficient to cause movement would cause the block to accelerate. Hence, the St. Venant element is always used in combination with the other basic elements.

The basic elements are usually combined in parallel or series to model material response. Figure 1.12 shows the three primary two-component models: the Maxwell, Kelvin, and Prandtl models. The Maxwell and Kelvin models have a spring and dashpot in series and parallel, respectively. The Prandtl model uses a spring and St. Venant elements in series.

In the *Maxwell* model [Figure 1.12(a)], the total deformation is the sum of the deformations of the individual elements. The force in each of the elements must be equal to the total force ($F = F_1 = F_2$). Thus, the equation for the total deformation at any time after a constant load is applied is simply:

$$\delta = \delta_1 + \delta_2 = \frac{F}{M} + \frac{Ft}{\beta} \tag{1.7}$$

In the *Kelvin* model, Figure 1.12(b), the deformation of each of the elements must be equal at all times due to the way the model is formulated. Thus, the total deformation is equal to the deformation of each element ($\delta = \delta_1 = \delta_2$). Since the elements are in parallel, they will share the force such that the total force is equal to the sum of the force in each element. If $\delta = 0$ at time $t = 0$ when a constant force F is applied, Equation 1.4 then requires zero force in the spring. Hence, when the load is initially applied, before any deformation takes place, all of the force must be in the dashpot. Under constant force the deformation of the dashpot must increase since there is force on the element. However, this also requires deformation of the spring, indicating that some of the force is carried by the spring. In fact, with time the amount of force in the dashpot decreases and the force in the spring increases. The proportion is fixed by the fact that the sum on the forces in the two elements must be equal to the total force. After a sufficient amount of time, all of the force will be transferred to the spring and the model will stop deforming. Thus the maximum deformation of the Kelvin model is $\delta = F/M$. Mathematically, the equation for the deformation in a Kelvin model is derived as:

$$F = F_1 + F_2 = M\delta + \beta\dot{\delta} \tag{1.8}$$

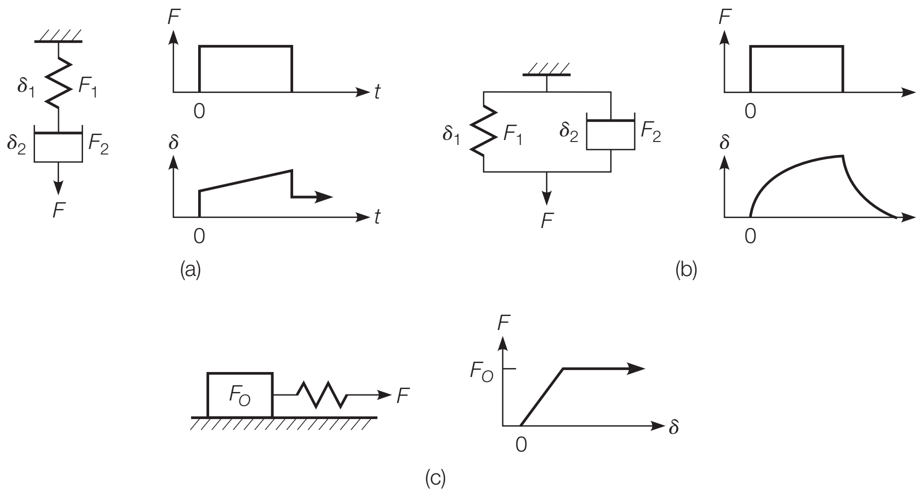

FIGURE 1.12 Two-element rheological models: (a) Maxwell, (b) Kelvin, and (c) Prandtl.

Integrating Equation 1.8, using the limits that $\delta = 0$ at $t = 0$, and solving for the deformation δ at time t results in

$$\delta = (F/M)(1 - e^{-Mt/\beta}) \tag{1.9}$$

The *Prandtl* model [Figure 1.12(c)] consists of St. Venant and Hookean bodies in series. The Prandtl model represents a material with an elastic–perfectly plastic response. If a small load is applied, the material responds elastically until it reaches the yield point, after which the material exhibits plastic deformation.

Neither the Maxwell nor Kelvin model adequately describes the behavior of some common engineering materials, such as asphalt concrete. However, the Maxwell and the Kelvin models can be put together in series, producing the *Burgers* model, which can be used to describe simplistically the behavior of asphalt concrete. As shown in Figure 1.13, the Burgers model is generally drawn as a spring in series with a Kelvin model in series with a dashpot. The total deformation at time t, with

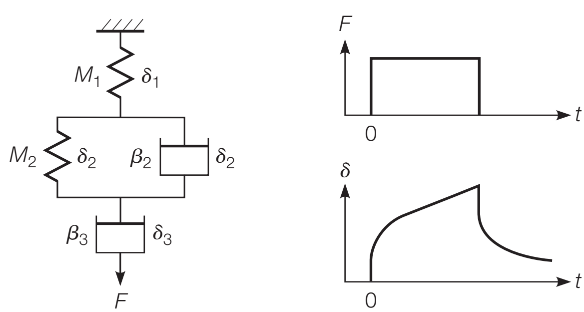

FIGURE 1.13 Burgers model of viscoelastic materials.

an initial point of $\delta = 0$ at time $t = 0$, is then the sum of the deformations at time t of these three elements.

$$\delta = \delta_1 + \delta_2 + \delta_3 = F/M_1 + (F/M_2)(1 - e^{-M_2 t/\beta_2}) + Ft/\beta_3 \tag{1.10}$$

The deformation-time diagram for the loading part of the Burgers model demonstrates three distinct phases of behavior. First is the instantaneous deformation of the spring when the load is applied. Second is the combined deformation of the Kelvin model and the dashpot. Third, after the Kelvin model reaches maximum deformation, there is a continued deformation of the dashpot at a constant rate of deformation. The unloading part of the Burgers model follows similar behavior.

Some materials require more complicated rheological models to represent their response. In such cases, a number of Maxwell models can be combined in parallel to form the generalized Maxwell model, or a number of Kelvin models in series can be used to form the generalized Kelvin model.

The use of rheological models requires quantifying material parameters associated with each model. Laboratory tests, such as creep tests, can be used to obtain deformation–time curves from which material parameters can be determined.

Although the rheological models are useful in describing the time-dependent response of materials, they can be used only to represent uniaxial responses. The three-dimensional behavior of materials and the Poisson's effect cannot be represented by these models.

Sample Problem 1.4

Derive the response relation for the following model assuming that the force *F* is constant and instantaneously applied.

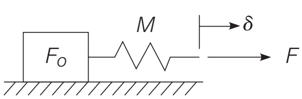

FIGURE SP1.4

Solution

For $F \leq F_o$: $\delta = F/M$

For $F > F_o$: movement

1.2.6 Temperature and Time Effects

The mechanical behavior of all materials is affected by temperature. Some materials, however, are more susceptible to temperature than others. For example, viscoelastic materials, such as plastics and asphalt, are greatly affected by temperature, even if the temperature is changed by only a few degrees. Other materials, such as metals or concrete, are less affected by temperatures, especially when they are near ambient temperature.

Ferrous metals, including steel, demonstrate a change from ductile to brittle behavior as the temperature drops below the *transition temperature*. This change

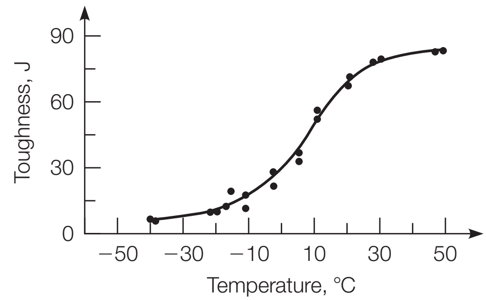

FIGURE 1.14 Fracture toughness of steel under impact testing.

from ductile to brittle behavior greatly reduces the toughness of the material. While this could be determined by evaluating the stress–strain diagram at different temperatures, it is more common to evaluate the toughness of a material with an impact test that measures the energy required to fracture a specimen. Figure 1.14 shows how the energy required to fracture a mild steel changes with temperature (Flinn and Trojan, 1995). The test results seen in Figure 1.14 were achieved by applying impact forces on bar specimens with a "defect" (a simple V notch) machined into the specimens (ASTM E23). During World War II, many Liberty ships sank because the steel used in the ships met specifications at ambient temperature, but became brittle in the cold waters of the North Atlantic.

In addition to temperature, some materials, such as viscoelastic materials, are affected by the load duration. The longer the load is applied, the larger is the amount of deformation or creep. In fact, increasing the load duration and increasing the temperature cause similar material responses. Therefore, temperature and time can be interchanged. This concept is very useful in running some tests. For example, a creep test on an asphalt concrete specimen can be performed with short load durations by increasing the temperature of the material. A *time–temperature shift factor* is then used to adjust the results for lower temperatures.

Viscoelastic materials are affected not only by the duration of the load but also by the rate of load application. If the load is applied at a fast rate, the material is stiffer than if the load is applied at a slow rate. For example, if a heavy truck moves at a high speed on an asphalt pavement, no permanent deformation may be observed. However, if the same truck is parked on an asphalt pavement on a hot day, some permanent deformations on the pavement surface may be observed.

1.2.7 Work and Energy

When a material is tested, the testing machine is actually generating a force in order to move or deform the specimen. Since work is force times distance, the area under a force–displacement curve is the work done on the specimen. When the force is divided by the cross-sectional area of the specimen to compute the stress, and the deformation is divided by the length of the specimen to compute the strain, the force–displacement diagram becomes a stress–strain diagram. However, the area under the stress–strain diagram no longer has the units of work. By manipulating the units of the stress–strain diagram, we can see that the area under the stress–strain

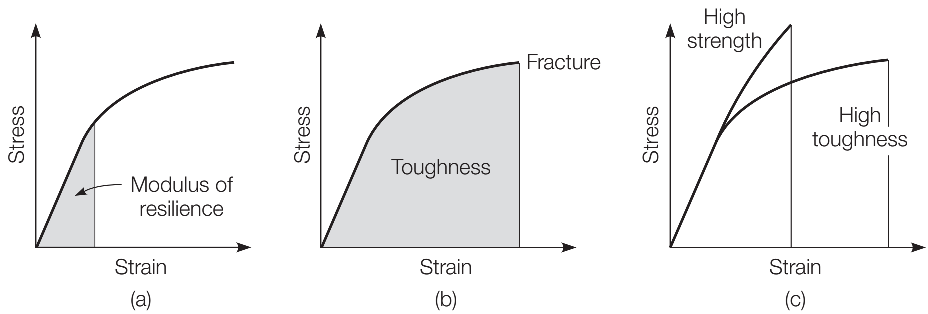

FIGURE 1.15 **Areas under stress–strain curves: (a) modulus of resilience, (b) toughness, and (c) high-strength and high-toughness materials.**

diagram equals the work per unit volume of material required to deform or fracture the material. This is a useful concept, for it tells us the energy that is required to deform or fracture the material. Such information is used for selecting materials to use where energy must be absorbed by the member. The area under the elastic portion of the curve is the *modulus of resilience* [Figure 1.15(a)]. The amount of energy required to fracture a specimen is a measure of the *toughness* of the material, as in Figure 1.15(b). As shown in Figure 1.15(c), a high-strength material is not necessarily a tough material. For instance, as discussed in Chapter 3, increasing the carbon content of steel increases the yield strength but reduces ductility. Therefore, the strength is increased, but the toughness may be reduced.

1.2.8 Failure and Safety

Failure occurs when a member or structure ceases to perform the function for which it was designed. Failure of a structure can take several modes, including fracture, fatigue, general yielding, buckling, and excessive deformation. *Fracture* is a common failure mode. A brittle material typically fractures suddenly when the static stress reaches the strength of the material, where the strength is defined as the maximum stress the material can carry. On the other hand, a ductile material may fracture due to excessive plastic deformation.

Many structures, such as bridges, are subjected to repeated loadings, creating stresses that are less than the strength of the material. Repeated stresses can cause a material to fail or *fatigue,* at a stress well below the strength of the material. The number of applications a material can withstand depends on the stress level relative to the strength of the material. As shown in Figure 1.16, as the stress level decreases, the number of applications before failure increases. Ferrous metals have an apparent *endurance limit,* or stress level, below which fatigue does not occur. The endurance limit for steels is generally in the range of one-quarter to one-half the ultimate strength (Flinn and Trojan, 1995). Another example of a structure that may fail due to fatigue is pavement. Although the stresses applied by traffic are typically much less than the strength of the material, repeated loadings may eventually lead to a loss of the structural integrity of the pavement surface layer, causing fatigue cracks as shown in Figure 1.17.

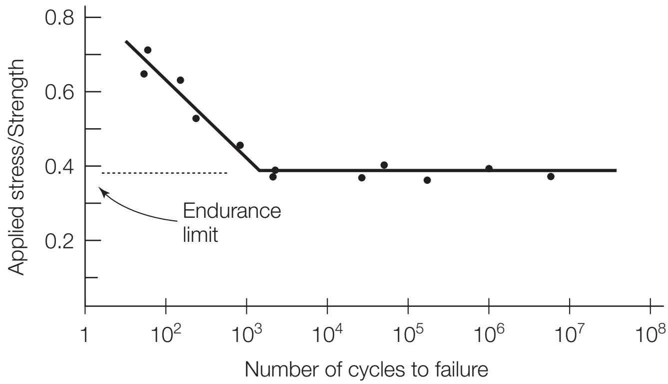

FIGURE 1.16 An example of endurance limit under repeated loading.

Another mode of failure is *general yielding*. This failure happens in ductile materials, and it spreads throughout the whole structure, which results in a total collapse.

Long and slender members subjected to axial compression may fail due to *buckling*. Although the member is intended to carry axial compressive loads, a small lateral force might be applied, which causes deflection and eventually might cause failure.

FIGURE 1.17 Fatigue failure of asphalt pavement due to repeated traffic loading.

Sometimes *excessive deformation* (elastic or plastic) could be defined as failure, depending on the function of the member. For example, excessive deflections of floors make people uncomfortable and, in an extreme case, may render the building unusable even though it is structurally sound.

To minimize the chance of failure, structures are designed to carry a load greater than the maximum anticipated load. The *factor of safety* (*FS*) is defined as the ratio of the stress at failure to the allowable stress for design (maximum anticipated stress):

$$FS = \frac{\sigma_{\text{failure}}}{\sigma_{\text{allowable}}} \tag{1.11}$$

where σ_{failure} is the failure stress of the material and $\sigma_{\text{allowable}}$ is the allowable stress for design. Typically, a high factor of safety requires a large structural cross section and consequently a higher cost. The proper value of the factor of safety varies from one structure to another and depends on several factors, including the

- cost of unpredictable failure in lives, dollars, and time,
- variability in material properties,
- degree of accuracy in considering all possible loads applied to the structure, such as earthquakes,
- possible misuse of the structure, such as improperly hanging an object from a truss roof,
- degree of accuracy of considering the proper response of materials during design, such as assuming elastic response although the material might not be perfectly elastic.

1.3 Nonmechanical Properties

Nonmechanical properties refer to characteristics of the material, other than load response, that affect selection, use, and performance. There are several types of properties that are of interest to engineers, but those of the greatest concern to civil engineers are density, thermal properties, and surface characteristics.

1.3.1 Density and Unit Weight

In many structures, the dead weight of the materials in the structure significantly contributes to the total design stress. If the weight of the materials can be reduced, the size of the structural members can also be reduced. Thus, the weight of the materials is an important design consideration. In addition, in the design of asphalt and concrete mixes, the weight–volume relationship of the aggregates and binders must be used to select the mix proportions.

There are three general terms used to describe the mass, weight, and volume relationship of materials. *Density* is the mass per unit volume of material. *Unit weight* is the weight per unit volume of material. By manipulation of units, it can be shown that

$$\gamma = \rho g \tag{1.12}$$

where
γ = unit weight
ρ = density
g = acceleration of gravity

Specific gravity is the ratio of the mass of a substance relative to the mass of an equal volume of water at a specified temperature. The density of water is 1 Mg/m^3 at 4°C. According to the definition, specific gravity is equivalent to the density of a material divided by the density of water. Since the density of water in the metric system has a numerical value of 1, the numerical value of density and specific gravity are equal. This fact is often used in the literature where density and specific gravity terms are used interchangeably.

For solid materials, such as metals, the unit weight, density, and specific gravity have definite numerical values. For other materials such as wood and aggregates, voids in the materials require definitions for a variety of densities and specific gravities. As shown in Figure 1.18(a) and (b), the bulk volume aggregates will occupy depends on the compaction state of the material. In addition, the density of the material will change depending on how the volume of individual particles is measured. Several types of particle volume can be used, such as the total volume enclosed within the boundaries of the individual particles, volume not accessible to water or asphalt, and volume of solids, as seen in Figure 1.18(c), (d), and (e), respectively. These are important factors in the mix designs of portland cement concrete and asphalt concrete.

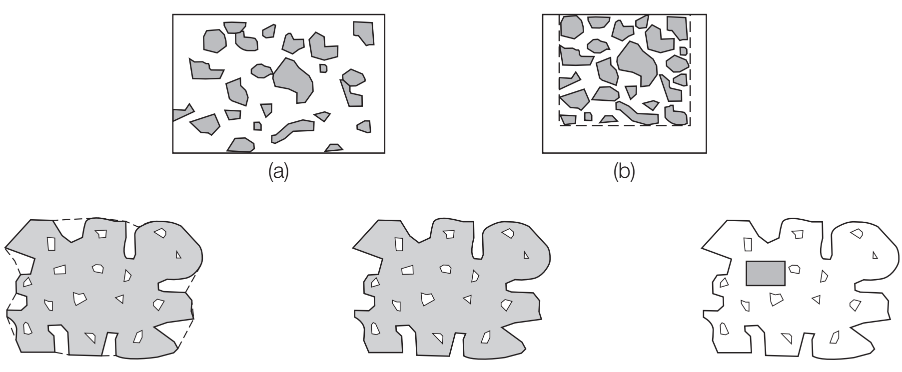

FIGURE 1.18 Definitions of volume used for determining density: (a) loose, (b) compacted, (c) total particle volume, (d) volume not accessible to water, and (e) volume of solids.

1.3.2 Thermal Expansion

Practically all materials expand as temperature increases and contract as temperature falls. The amount of expansion per unit length due to one unit of temperature increase is a material constant and is expressed as the *coefficient of thermal expansion*

$$\alpha_L = \frac{\delta L / dT}{L} \tag{1.13}$$

$$\alpha_V = \frac{\delta V / dT}{V} \tag{1.14}$$

where

α_L = linear coefficient of thermal expansion
α_V = volumetric coefficient of thermal expansion
δL = change in the length of the specimen
δT = change in temperature
L = original length of the specimen
δV = change in the volume of the specimen
V = original volume of the specimen

For isotropic materials, $\alpha_V = 3\alpha_L$.

The coefficient of thermal expansion is very important in the design of structures. Generally, structures are composed of many materials that are bound together. If the coefficients of thermal expansion are different, the materials will strain at different rates. The material with the lesser expansion will restrict the straining of other materials. This constraining effect will cause stresses in the materials that can lead directly to fracture.

Stresses can also be developed as a result of a thermal gradient in the structure. As the temperature outside the structure changes and the temperature inside remains constant, a thermal gradient develops. When the structure is restrained from straining, stress develops in the material. This mechanism has caused brick facades on buildings to fracture and, in some cases, fall off the structure. Also, since concrete pavements are restrained from movement, they may crack in the winter due to a drop in temperature and may "blow up" in the summer due to an increase in temperature. Joints are, therefore, used in buildings, bridges, concrete pavements, and various structures to accommodate this thermal effect.

Sample Problem 1.5

A steel bar with a length of 3 m, diameter of 25 mm, modulus of elasticity of 207 GPa, and linear coefficient of thermal expansion of 0.000009 m/m/°C is fixed at both ends when the ambient temperature is 40°C. If the ambient temperature is decreased to 15°C, what internal stress will develop due to this temperature change? Is this stress tension or compression? Why?

Solution

If the bar was fixed at one end and free at the other end, the bar would have contracted and no stresses would have developed. In that case, the change in length can be calculated by using Equation 1.13 as follows:

$$\delta L = \alpha_L \times \delta T \times L = 0.000009 \times (-25) \times 3 = -0.000675 \text{ m}$$
$$\varepsilon = \delta L/L = -0.000675/3 = -0.000225 \text{ m/m}$$

Since the bar is fixed at both ends, the length of the bar will not change. Therefore, a tensile stress will develop in the bar as follows:

$$\sigma = \varepsilon E = 0.000225 \times 207000 = 46.575 \text{ MPa}$$

The stress will be tension; in effect, the length of the bar at 15°C without restraint would be 2.999325 m and the stress would be zero. Restraining the bar into a longer condition requires a tensile force.

1.3.3 Surface Characteristics

The surface properties of materials of interest to civil engineers include corrosion and degradation, the ability of the material to resist abrasion and wear, and surface texture.

Corrosion and Degradation Nearly all materials deteriorate over their service lives. The mechanisms contributing to the deterioration of a material differ depending on the characteristics of the material and the environment. Crystalline materials, such as metals and ceramics, deteriorate through a *corrosion* process in which there is a loss of material, either by dissolution or by the formation of nonmetallic scale or film. Polymers, such as asphalt, deteriorate by *degradation* of the material, including the effects of solvent and ultraviolet radiation on the material.

The protection of materials from environmental degradation is an important design concern, especially when the implications of deterioration and degradation on the life and maintenance costs of the structure are considered. The selection of a material should consider both how the material will react with the environment and the cost of preventing the resulting degradation.

Abrasion and Wear Resistance Since most structures in civil engineering are static, the abrasion or wear resistance is of less importance than in other fields of engineering. For example, mechanical engineers must be concerned with the wear of parts in the design of machinery. This is not to say that wear resistance can be totally ignored in civil engineering. Pavements must be designed to resist the wear and polishing from vehicle tires in order to provide adequate skid resistance for braking and turning. Resistance to abrasion and wear is, therefore, an important property of aggregates used in pavements.

Surface Texture The surface texture of some materials and structures is of importance to civil engineers. For example, smooth texture of aggregate particles is needed in portland cement concrete to improve workability during mixing and placing. In contrast, rough texture of aggregate particles is needed in asphalt concrete mixtures to provide a stable pavement layer that resists deformation under the action of load. Also, a certain level of surface texture is needed in the pavement surface to provide adequate friction resistance and prevent skidding of vehicles when the pavement is wet.

1.4 Production and Construction

Even if a material is well suited to a specific application, production and construction considerations may block the selection of the material. Production considerations include the availability of the material and the ability to fabricate the material into the desired shapes and required specifications. Construction considerations address all the factors that relate to the ability to fabricate and erect the structure on site. One of the primary factors is the availability of a trained work force. For example, in some cities, high-strength concrete is used for skyscrapers, whereas in other cities, steel is the material of choice. Clearly, either concrete or steel can be used for high-rise buildings. Regional preferences for one material develop as engineers in the region become comfortable and confident in designing with one of the materials and constructors respond with a trained work force and specialized equipment.

1.5 Aesthetic Characteristics

The aesthetic characteristics of a material refer to the appearance of the material. Generally, these characteristics are the responsibility of the architect. However, the civil engineer is responsible for working with the architect to ensure that the aesthetic characteristics of the facility are compatible with the structural requirements. During the construction of many public projects, a certain percentage of the capital budget typically goes toward artistic input. The collaboration between the civil engineer and the architect is greatly encouraged, and the result can increase the value of the structure (see Figure 1.19).

In many cases, the mix of artistic and technical design skills makes the project acceptable to the community. In fact, political views are often more difficult to deal with than technical design problems. Thus, engineers should understand that there are many factors beyond the technical needs that must be considered when selecting materials and designing public projects.

FIGURE 1.19 An example of artist-engineer collaboration in an engineering project: Air Force Academy, Colorado Springs, Colorado.

1.6 Sustainable Design

Sustainable design is the philosophy of designing physical objects, the built environment and services to comply with the principles of economic, social, and ecological sustainability. Specifically, civil and construction engineers should be concerned with design and construction decisions which are sensitive to both the current and future needs of society. Some owners are mandating the use of a building assessment system for design, construction, and long-term performance. Since 2003, the General Services Administration, GSA, in the United States, has required a sustainablility rating of all building projects (Fowler and Rauch, 2006). With the emphasis on sustainability, several rating systems have been developed including:

- BREEAM (Building Research Establishment's Environmental Assessment Method) developed in the United Kingdom.
- CASBEE (Comprehensive Assessment System for Building Environmental Efficiency) developed in Japan.
- GBTool an internationally developed system that was initially developed in 1998 and has undergone multiple revisions.

- Green Globes™ developed in Cananda based on the BREEAM method. A US version has been developed by the Green Building Initiative.
- LEED® (Leadership in Energy and Environmental Design).
- Living Building Challenge.

The LEED system is the most widely used with thousands of users (Wang et al., 2012) so it is the only one reviewed in this text.

The materials used for a civil engineering project are a fundamental consideration for determining the sustainability of a project. While sustainable design is a philosophy, implementation of the concept requires direct and measureable actions.

To this end, the Green Building Council developed the Leadership in Environment and Energy Design, LEED, building rating system (LEED, 2013).

The LEED rating system is used to evaluate the sustainability of a project. Elements of the project are rated in several areas. Based on the cumulative rating, the project is awarded a status of Certified, Silver, Gold, or Platinum. For new construction and major renovations, the rating areas include:

- Sustainable sites
- Water efficiency
- Energy and atmosphere
- Materials and resources
- Indoor environmental quality
- Innovation in design
- Regional priority

There is an obvious connection between this book and the Materials and Resources area of LEED. The items considered in the Materials and Resource area include:

- Storage and collection of recyclables
- Building reuse–maintain existing walls, floors and roof, interior walls, and nonstructural elements
- Construction waste management
- Materials reuse
- Recycled content
- Regional materials
- Rapidly renewable materials
- Certified wood

If an owner wishes to pursue a specific level of LEED certification, the engineer is charged with the responsibility of selecting materials that meet the functional requirements of the building and provide the desired LEED rating. For example, by selecting regional materials, the LEED rating is increased and there may be little or no impact on the cost of the facility.

In addition to the direct tie to the materials and resources, there are other areas of the LEED certification that are affected by material selection. Selection of engineered wood products which are fabricated with glues rated for low off gassing of volatile organic compounds, VOCs, improves the LEED score with respect to Indoor Environmental Quality. Selection of a porous pavement surface for parking lots improves the LEED score for site development.

It should be noted that the LEED rating system is for the certification of buildings, not the materials that are used for construction. Manufactures can seek third party certification of their products to use as evidence that these products support a claim for LEED credits. Environmental and health reviews and certifications are available from a variety of organizations such as Scientific Certification Systems, Forest Stewardship Council, Building Green Inc., Green Seal, Green Guard, Building Green, etc (USGBC, 2015).

1.7 Material Variability

It is essential to understand that engineering materials are inherently variable. For example, steel properties vary depending on chemical composition and method of manufacture. Concrete properties change depending on type and amount of cement, type of aggregate, air content, slump, method of curing, etc. The properties of asphalt concrete vary depending on the binder amount and type, aggregate properties and gradation, amount of compaction, and age. Wood properties vary depending on the tree species, method of cut, and moisture content. Some materials are more homogeneous than others, depending on the nature of the material and the method of manufacturing. For example, the variability of the yield strength of one type of steel is less than the variability of the compressive strength of one batch of concrete. Therefore, variability is an important parameter in defining the quality of civil engineering materials.

When materials from a particular lot are tested, the observed variability is the cumulative effect of three types of variance: the inherent variability of the material, variance caused by the sampling method, and variance associated with the way the tests was conducted. Just as materials have an inherent variability, sampling procedures and test methods can produce variable results. Frequently, statisticians call variance associated with sampling and testing *error*. However, this does not imply the sampling or testing was performed incorrectly. When an incorrect procedure is identified, it is called a *blunder*. The goal of a sampling and testing program is to minimize sampling and testing variance so the true statistical features of the material can be identified.

The concepts of precision and accuracy are fundamental to the understanding of variability. *Precision* refers to the variability of repeat measurements under carefully controlled conditions. *Accuracy* is the conformity of results to the true value or the absence of bias. *Bias* is a tendency of an estimate to deviate in one direction from the true value. In other words, bias is a systematic error between a test value and the true value. A simple analogy to the relationship between precision and accuracy is the target shown in Figure 1.20. When all shots are concentrated at one location away from the center, that indicates good precision and poor accuracy (biased) [Figure 1.20(a)]. When shots are scattered around the center, that indicates poor precision and good accuracy [Figure 1.20(b)]. Finally, good precision and good accuracy are obtained if all shots are concentrated close to the center [Figure 1.20(c)] (Burati and Hughes, 1990). Many standardized test methods, such as those of the