Chapter 18

Construction Materials

Have You Ever Wondered?

- *What are the most widely used manufactured construction materials?*
- *What is the difference between cement and concrete?*
- *What construction material is a composite made by nature?*
- *What is reinforced concrete?*

A number of important materials are used in the construction of buildings, highways, bridges, and much of our country's infrastructure. In this chapter, we examine three of the most important of these materials: wood, concrete, and asphalt. The field of construction materials is indeed very important for engineers, especially civil engineers and highway engineers. The properties and processing of steels used for making reinforced concrete, ceramics (e.g., sand, lime, concrete), plastics (e.g., epoxies and polystyrene foams), glasses, and composites (e.g., fiberglass) play a critical role in the development and use of construction materials. Another area in civil engineering that is becoming increasingly important is related to the use of sensors and actuators in buildings and bridges. Advanced materials developed for microelectronic and optical applications play an important role in this area.

For example, smart bridges and buildings that make use of optical fiber sensors currently are being developed. These sensors can monitor the health of the structures on a continuous basis and thus can provide early warnings of any potential problems. Similarly, researchers in areas of smart structures are also working on many other ideas using sensors that can detect things such as the formation of ice. If ice is detected, the system can start to spray salt water to prevent or delay freezing. Sensors such as this are also installed on steep driveways in some commercial parking garages where activation of the snow/ice sensors initiates heating of that part of the driveway. Similarly, we now have many smart coatings on glasses that can deflect heat and make buildings energy efficient.

There are new coatings that have resulted in self-cleaning glasses. New technologies are also being implemented to develop "green buildings."

There are many other areas of materials that relate to structures. For example, the corrosion of bridges and the limitations it poses on the bridge's life expectancy is a major cost for any nation. Strategies using galvanized steels and the proper paints to protect against corrosion are crucial aspects of bridges design. Similarly, many material joining techniques, such as welding, play a very important role in the construction of bridges and buildings. Long-term environmental impacts of the materials used must be considered (e.g., what are the best materials to use for water pipes, insulation, fire retardancy, etc.?). The goal of this chapter is to present a summary of the properties of wood, concrete, and asphalt.

18-1 The Structure of Wood

Wood, a naturally occuring composite, is one of our most familiar materials. Although it is not a "high-tech" material, we are literally surrounded by it in our homes and value it for its beauty and durability. In addition, wood is a strong, lightweight material that still dominates much of the construction industry.

We can consider wood to be a complex fiber-reinforced composite composed of long, unidirectionally aligned, tubular polymer cells in a polymer matrix. Furthermore, the polymer tubes are composed of bundles of partially crystalline, cellulose fibers aligned at various angles to the axes of the tubes. This arrangement provides excellent tensile properties in the longitudinal direction.

Wood consists of four main constituents. **Cellulose** fibers make up about 40% to 50% of wood. Cellulose is a naturally occurring thermoplastic polymer with a degree of polymerization of about 10,000. The structure of cellulose is shown in Figure 18-1. About 25% to 35% of a tree is **hemicellulose**, a polymer having a degree of polymerization of about 200. Another 20% to 30% of a tree is **lignin**, a low molecular weight, organic cement that bonds the various constituents of the wood. Finally, **extractives** are organic impurities such as oils, which provide color to the wood or act as preservatives against the environment and insects, and inorganic minerals such as silica, which dull saw blades during the cutting of wood. As much as 10% of the wood may be extractives.

There are three important levels in the structure of wood: the fiber structure, the cell structure, and the macrostructure (Figure 18-2).

Fiber Structure

The basic component of wood is cellulose, $C_6H_{10}O_5$, arranged in polymer chains that form long fibers. Much of the fiber length is crystalline,

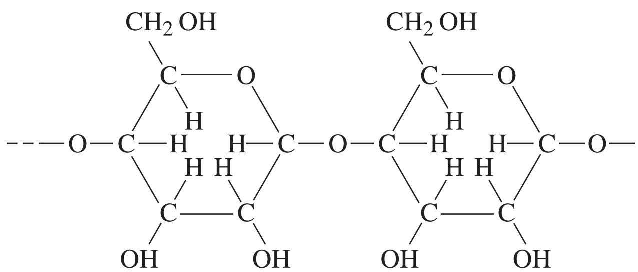


Figure 18-1
The structure of the cellulose filaments in wood.

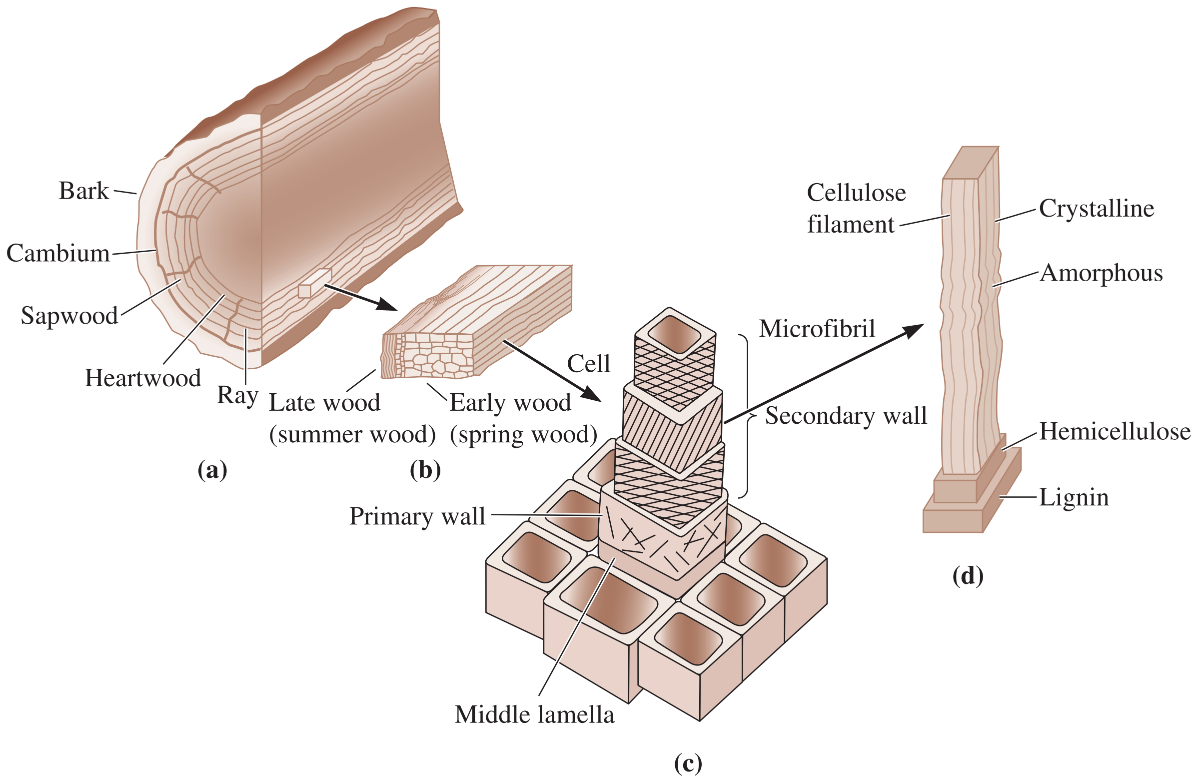
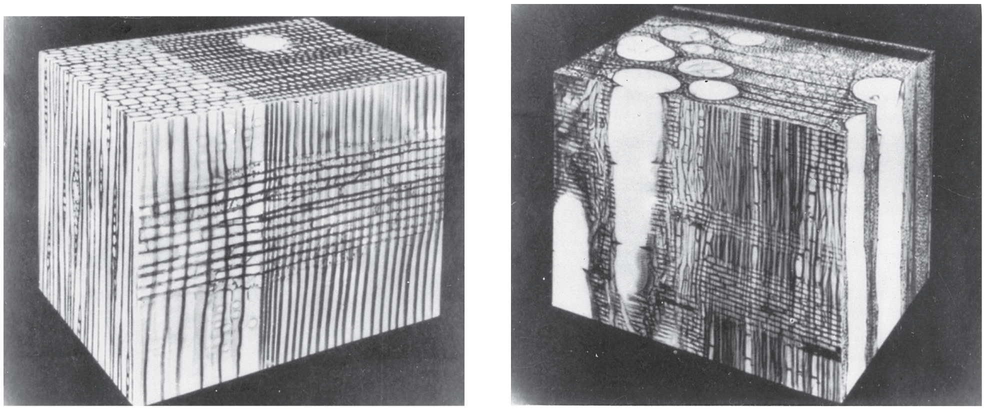


Figure 18-2 The structure of wood: (a) the macrostructure, including a layer structure outlined by the annual growth rings, (b) detail of the cell structure within one annual growth ring, (c) the structure of a cell, including several layers composed of microfibrils of cellulose fibers, hemicellulose fibers, and lignin, and (d) the microfibril's aligned, partly crystalline cellulose chains.

with the crystalline regions separated by small lengths of amorphous cellulose. A bundle of cellulose chains are encased in a layer of randomly oriented, amorphous hemicellulose chains. Finally, the hemicellulose is covered with lignin [Figure 18-2(d)]. The entire bundle, consisting of cellulose chains, hemicellulose chains, and lignin, is called a **microfibril**; it can have a virtually infinite length.

Cell Structure The tree is composed of elongated cells, often having an aspect ratio of 100 or more, that constitute about 95% of the solid material in wood. The hollow cells are composed of several layers built up from the microfibrils [Figure 18-2(c)]. The first, or primary, wall of the cell contains randomly oriented microfibrils. As the cell walls thicken, three more distinct layers are formed. The outer and inner walls contain microfibrils oriented in two directions that are not parallel to the cell. The middle wall, which is the thickest, contains microfibrils that are unidirectionally aligned, usually at an angle not parallel to the axis of the cell.

Macrostructure A tree is composed of several layers [Figure 18-2(a)]. The outer layer, or *bark*, protects the tree. The **cambium**, just beneath the bark, contains new growing cells. The **sapwood** contains a few hollow living cells that store nutrients and serve as the conduit for water. Finally, the **heartwood**, which contains only dead cells, provides most of the mechanical support for the tree.



(a) (b)

Figure 18-3 The cellular structure in (a) softwood and (b) hardwood. Softwoods contain larger, longer cells than hardwoods. The hardwoods, however, contain large-diameter vessels. Water is transported through softwoods by the cells and through hardwoods by the vessels. *(From J.M. Dinwoodie,* Wood: Nature's Cellular Polymeric Fiber-Composite, *The Institute of Metals, 1989.)*

The tree grows when new elongated cells develop in the cambium. Early in the growing season, the cells are large; later they have a smaller diameter, thicker walls, and a higher density. This difference between the early (or *spring*) wood and the late (or *summer*) wood permits us to observe annual growth rings [Figure 18-2(b)]. In addition, some cells grow in a radial direction; these cells, called *rays*, provide the storage and transport of food.

Hardwood Versus Softwood

The hardwoods are deciduous trees such as oak, ash, hickory, elm, beech, birch, walnut, and maple. In these trees, the elongated cells are relatively short, with a diameter of less than 0.1 mm and a length of less than 1 mm. Contained within the wood are longitudinal pores, or vessels, which carry water through the tree (Figure 18-3).

The softwoods are the conifers, evergreens such as pine, spruce, hemlock, fir, spruce, and cedar, and have similar structures. In softwoods, the cells tend to be somewhat longer than in the hardwoods. The hollow center of the cells is responsible for transporting water. In general, the density of softwoods tends to be lower than that of hardwoods because of a greater percentage of void space.

18-2 Moisture Content and Density of Wood

The material making up the individual cells in virtually all woods has essentially the same density—about 1.45 g/cm^3; however, wood contains void space that causes the actual density to be much lower. The density of wood depends primarily on the species of the tree (or the amount of void space peculiar to that species) and the percentage of water in the wood (which depends on the amount of drying and on the relative humidity to which the wood is exposed during use). Completely dry wood varies in density from about 0.3 to 0.8 g/cm^3, with hardwoods having higher densities than softwoods. The measured

TABLE 18-1 ■ *Properties of typical woods*

Wood	Density (for 12% Water) (g/cm^3)	Modulus of Elasticity (MPa)
Cedar	0.32	7,600
Pine	0.35	8,300
Fir	0.48	13,800
Maple	0.48	10,350
Birch	0.62	13,800
Oak	0.68	12,400

density is normally higher due to the water contained in the wood. The percentage water is given by

$$\% \text{ Water} = \frac{\text{weight of water}}{\text{weight of dry wood}} \times 100 \tag{18-1}$$

On the basis of this definition, it is possible to describe a wood as containing more than 100% water. The water is contained both in the hollow cells or vessels, where it is not tightly held, and in the cellulose structure in the cell walls, where it is more tightly bonded to the cellulose fibers. While a large amount of water is stored in a live tree, the amount of water in the wood after the tree is harvested depends, eventually, on the humidity to which the wood is exposed; higher humidity increases the amount of water held in the cell walls. The density of a wood is usually given at a moisture content of 12%, which corresponds to 65% humidity. The density and modulus of elasticity parallel to the grain of several common woods are included in Table 18-1 for this typical water content.

The following example illustrates the calculation for the density of the wood.

Example 18-1 *Density of Dry and Wet Wood*

A green wood has a density of 0.86 g/cm^3 and contains 175% water. Calculate the density of the wood after it has completely dried.

SOLUTION

A 100-cm^3 sample of the wood would have a mass of 86 g. From Equation 18-1, we can calculate the weight (or in this case, mass) of the dry wood to be

$$\% \text{ Water} = \frac{\text{weight of water}}{\text{weight of dry wood}} \times 100 = 175$$

$$= \frac{\text{green weight} - \text{dry weight}}{\text{dry weight}} \times 100 = 175$$

Solving for the dry weight of the wood:

$$\text{Dry weight of wood} = \frac{(100)(\text{green weight})}{275}$$

$$= \frac{(100)(86)}{275} = 31.3 \text{ g}$$

$$\text{Density of dry wood} = \frac{31.3 \text{ g}}{100 \text{ cm}^3} = 0.313 \text{ g/cm}^3$$

18-3 Mechanical Properties of Wood

The strength of a wood depends on its density, which in turn depends on both the water content and the type of wood. As a wood dries, water is eliminated first from the vessels and later from the cell walls. As water is removed from the vessels, practically no change in the strength or stiffness of the wood is observed (Figure 18-4). On continued drying to less than about 30% water, there is water loss from the actual cellulose fibers. This loss permits the individual fibers to come closer together, increasing the bonding between the fibers and the density of the wood and, thereby, increasing the strength and stiffness of the wood.

The type of wood also affects the density. Because they contain less of the higher-density late wood, softwoods typically are less dense and therefore have lower strengths than hardwoods. In addition, the cells in softwoods are larger, longer, and more open than those in hardwoods, leading to lower density.

The mechanical properties of wood are highly anisotropic. In the longitudinal direction (Figure 18-5), an applied tensile load acts parallel to the microfibrils and cellulose chains in the middle section of the secondary wall. These chains are strong—because they are mostly crystalline—and are able to carry a relatively high load. In the radial and

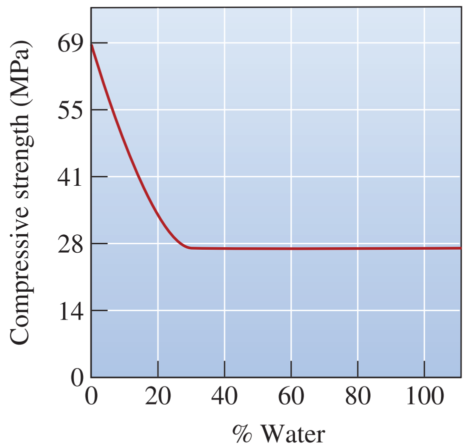


Figure 18-4
The effect of the percentage of water in a typical wood on the compressive strength parallel to the grain.

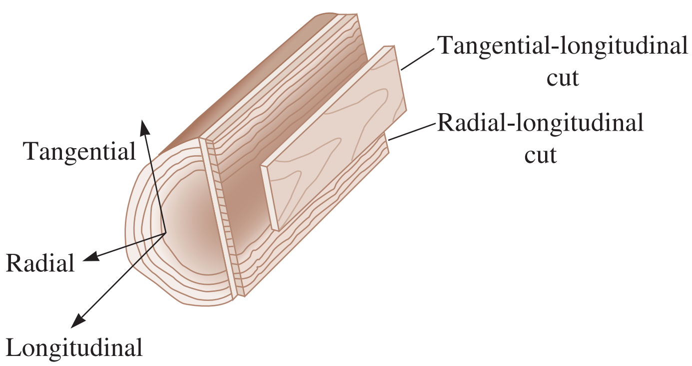


Figure 18-5
The different directions in a log. Because of differences in cell orientation and the grain, wood displays anisotropic behavior.

TABLE 18-2 ■ *Anisotropic behavior of several woods (at 12% moisture)*

	Tensile Strength Longitudinal (MPa)	Tensile Strength Radial (MPa)	Compressive Strength Longitudinal (MPa)	Compressive Strength Radial (MPa)
Beech	86	7	50	7
Elm	121	4.6	38	4.8
Maple	108	8	54	10
Oak	78	6.5	43	6
Cedar	46	2.2	42	6.3
Fir	78	2.7	37.6	4.2
Pine	73	2.1	33	3
Spruce	59	2.6	39	4

tangential directions, however, the weaker bonds between the microfibrils and cellulose fibers may break, resulting in very low tensile properties. Similar behavior is observed in compression and bending loads. Because of the anisotropic behavior, most lumber is cut in a tangential-longitudinal or radial-longitudinal manner. These cuts maximize the longitudinal behavior of the wood.

Wood has poor properties in compression and bending (which produces a combination of compressive and tensile forces). In compression, the fibers in the cells tend to buckle, causing the wood to deform and break at low stresses. Unfortunately, most applications for wood place the component in compression or bending and therefore do not take full advantage of the engineering properties of the material. Similarly, the modulus of elasticity is highly anisotropic; the modulus perpendicular to the grain is about 1/20th that given in Table 18-1 parallel to the grain. Table 18-2 compares the tensile and compressive strengths parallel and perpendicular to the cells for several woods.

Clear wood, free of imperfections such as knots, has a specific strength and specific modulus that compare well with those of other common construction materials (Table 18-3). Wood also has good toughness, largely due to the slight misorientation of the cellulose fibers in the middle layer of the secondary wall. Under load, the fibers straighten, permitting some ductility and energy absorption. The mechanical properties of wood also depend on imperfections in the wood. Clear wood may have a longitudinal tensile strength of 69 to 138 MPa. Less expensive construction lumber, which usually contains many imperfections, may have a tensile strength below 34 MPa. The knots also disrupt the grain of the wood in the vicinity of the knot, causing the cells to be aligned perpendicular to the tensile load.

TABLE 18-3 ■ *Comparison of the specific strength and specific modulus of wood with those of other common construction materials*

Material	Specific Strength ($\times 10^5$ cm)	Specific Modulus ($\times 10^7$ cm)
Clear wood	17.5	23.8
Aluminum	12.5	26.3
1020 steel	5	26.3
Copper	3.8	13.8
Concrete	1.5	8.8

After F.F. Wangaard, "Wood: Its Structure and Properties," J. Educ. Models for Mat. Sci. and Engr., *Vol. 3, No. 3, 1979.*

18-4 Expansion and Contraction of Wood

Like other materials, wood changes dimensions when heated or cooled. Dimensional changes in the longitudinal direction are very small in comparison with those in metals, polymers, and ceramics; however, the dimensional changes in the radial and tangential directions are greater than those for most other materials.

In addition to dimensional changes caused by temperature fluctuations, the moisture content of the wood causes significant changes in dimension. Again, the greatest changes occur in the radial and tangential directions, where the moisture content affects the spacing between the cellulose chains in the microfibrils. The change in dimensions Δx in wood in the radial and tangential directions is approximated by

$$\Delta x = x_0[c(M_f - M_i)] \tag{18-2}$$

where x_0 is the initial dimension, M_i is the initial water content, M_f is the final water content, and c is a coefficient that describes the dimensional change and can be measured in either the radial or the tangential direction. Table 18-4 includes the dimensional coefficients for several woods. In the longitudinal direction, no more than 0.1% to 0.2% change is observed.

During the initial drying of wood, the large dimensional changes perpendicular to the cells may cause warping and even cracking. In addition, when the wood is used, its water content may change, depending on the relative humidity in the environment. As the wood gains or loses water during use, shrinkage or swelling continues to occur. If a wood construction does not allow movement caused by moisture fluctuations, warping and cracking can occur—a particularly severe condition in large expanses of wood, such as the floor of a large room. Excessive expansion may cause large bulges in the floor; excessive shrinkage may cause large gaps between individual planks of the flooring.

TABLE 18-4 ■ ***Dimensional coefficient c (cm/cm·% H_2O) for several woods***

Wood	Radial	Tangential
Beech	0.00190	0.00431
Elm	0.00144	0.00338
Maple	0.00165	0.00353
Oak	0.00183	0.00462
Cedar	0.00111	0.00234
Fir	0.00155	0.00278
Pine	0.00141	0.00259
Spruce	0.00148	0.00263

18-5 Plywood

The anisotropic behavior of wood can be reduced and wood products can be made in larger sizes by producing plywood. Thin layers of wood, called **plies,** are cut from logs—normally, softwoods. The plies are stacked together with the grains between adjacent plies oriented at 90° angles; usually an odd number of plies is used. Ensuring that these angles are as precise as possible is important to ensure that the plywood does not warp or twist when the moisture content in the material changes. The individual plies are generally bonded to one another using a thermosetting phenolic resin. The resin is introduced between the plies, which are then pressed together while hot to cause the resin to polymerize.

Similar wood products are also produced as "laminar" composite materials. The facing (visible) plies may be of a more expensive hardwood with the center plies of a less expensive softwood. Wood particles can be compacted into sheets and laminated between two wood plies, producing a particle board. Wood plies can be used as the facings for honeycomb materials.

18-6 Concrete Materials

An **aggregate** is a combination of gravel, sand, crushed stones, or slag. A **mortar** is made by mixing cement, water, air, and fine aggregate. Concrete contains all of the ingredients of the mortar and coarse aggregates. **Cements** are inorganic materials that set and harden after being mixed into a paste using water. **Concrete** is a particulate composite in which both the particulate and the matrix are ceramic materials. In concrete, sand and a coarse aggregate are bonded in a matrix of **Portland cement**. A cementation reaction between water and the minerals in the cement provides a strong matrix that holds the aggregate in place and provides good compressive strength to the concrete.

Cements

Cements are classified as hydraulic and nonhydraulic. **Hydraulic cements** set and harden under water. **Nonhydraulic cements** (e.g., lime, CaO) cannot harden under water and require air for hardening. Portland cement is the most widely used and manufactured construction material. It was patented by Joseph Aspdin in 1824 and is named as such after the limestone cliffs on the Isle of Portland in England.

Hydraulic cement is made from calcium silicates with an approximate composition of CaO (~60 to 65%), SiO_2 (~20 to 25%), and iron oxide and alumina (~7 to 12%). The cement binder, which is very fine in size, is composed of various ratios of $3CaO \cdot Al_2O_3$, $2CaO \cdot SiO_2$, $3CaO \cdot SiO_2$, $4CaO \cdot Al_2O_3 \cdot Fe_2O_3$, and other minerals. In the cement terminology, CaO, SiO_2, Al_2O_3, and Fe_2O_3 are often indicated as *C*, *S*, *A*, and *F*, respectively. Thus, C_3S means $3CaO\text{-}SiO_2$. When water is added to the cement, a hydration reaction occurs, producing a solid gel that bonds the aggregate particles. Possible reactions include

$$3CaO \cdot Al_2O_3 + 6H_2O \rightarrow Ca_3Al_2(OH)_{12} + \text{heat}$$

$$3CaO + SiO_2 + (x + 1)H_2O \rightarrow Ca_2SiO_4 \cdot xH_2O + Ca(OH)_2 + \text{heat}$$

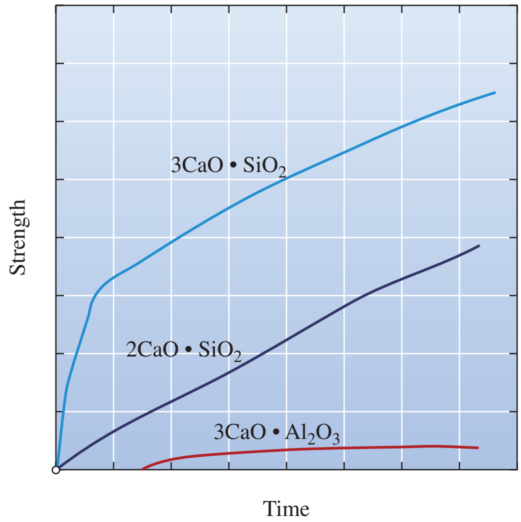


Figure 18-6
The rate of hydration of the minerals in Portland cement. (Based on Lea, Chemistry of Cement and Concrete, p. 286.)

After hydration, the cement provides the bond for the aggregate particles. Consequently, enough cement must be added to coat all of the aggregate particles. The cement typically constitutes on the order of 15 vol% of the solids in the concrete.

The composition of the cement helps determine the rate of curing and the final properties of the concrete, as shown in Figure 18-6. Nearly complete curing of the concrete is normally expected within 28 days (Figure 18-7), although some additional curing may continue for years.

There are about ten general types of cements used. Some are shown in Table 18-5. In large structures such as dams, curing should be slow in order to avoid excessive heating

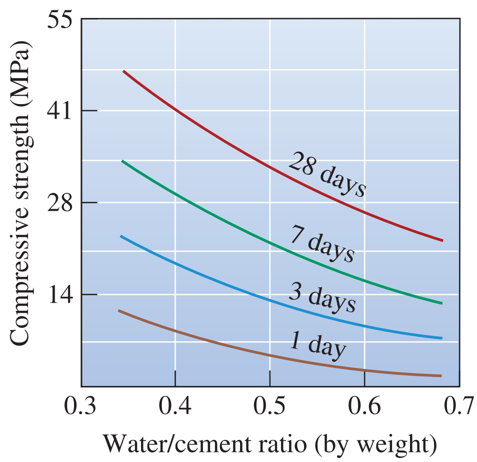


Figure 18-7
The compressive strength of concrete increases with time. After 28 days, the concrete approaches its maximum strength.

TABLE 18-5 ■ *Types of Portland cements*

	Approximate Composition				
	3C · S	2C · S	3C · A	4C · A · F	Characteristics
Type I	55	20	12	9	General purpose
Type II	45	30	7	12	Low rate of heat generation, moderate resistance to sulfates
Type III	65	10	12	8	Rapid setting
Type IV	25	50	5	13	Very low rate of heat generation
Type V	40	35	3	14	Good sulfate resistance

TABLE 18-6 ■ *Characteristics of concrete materials*

Material	True Density	
Cement	3 g/cm^3	1 sack = 42.6 kg
Sand	2.6 g/cm^3	
Aggregate	2.7 g/cm^3	Normal
	1.3 g/cm^3	Lightweight slag
	0.5 g/cm^3	Lightweight vermiculite
	4.5 g/cm^3	Heavy Fe_3O_4
	6.2 g/cm^3	Heavy ferrophosphorus
Water	1 g/cm^3	1.05×10^{-3} liters/cm^3

caused by the hydration reaction. These cements typically contain low percentages of $3CaO \cdot SiO_2$, such as in Types II and IV. Some construction jobs, however, require that concrete forms be removed and reused as quickly as possible; cements for these purposes may contain large amounts of $3CaO \cdot SiO_2$, as in Type III.

The composition of the cement also affects the resistance of the concrete to the environment. For example, sulfates in the soil may attack the concrete; using higher proportions of $4CaO \cdot Al_2O_3 \cdot Fe_2O_3$ and $2CaO \cdot SiO_2$ helps produce concretes more resistant to sulfates, as in Type V.

Sand Chemically, sand is predominantly silica (SiO_2). Sands are composed of fine mineral particles, typically of the order of 0.1 to 1.0 mm in diameter. They often contain at least some adsorbed water, which should be taken into account when preparing a concrete mix. The sand helps fill voids between the coarser aggregate, giving a high packing factor, reducing the amount of open (or interconnected) porosity in the finished concrete, and reducing problems with disintegration of the concrete due to repeated freezing and thawing during service.

Aggregate Coarse aggregate is composed of gravel and rock. Aggregate must be clean, strong, and durable. Aggregate particles that have an angular rather than a round shape provide strength due to mechanical interlocking between particles, but angular particles also provide more surface on which voids or cracks may form. It is normally preferred that the aggregate size be large; this condition also minimizes the surface area at which cracks or voids form. The size of the aggregate must, of course, be matched to the size of the structure being produced; aggregate particles should not be any larger than about 20% of the thickness of the structure.

In some cases, special aggregates may be used. Lightweight concretes can be produced by using mineral slags, which are produced during steel making operations; these concretes have improved thermal insulation. Particularly heavy concretes can be produced using dense minerals or even metal shot; these heavy concretes can be used in building nuclear reactors to better absorb radiation. The densities of several aggregates are included in Table 18-6.

18-7 Properties of Concrete

Many factors influence the properties of concrete. Some of the most important are the water-cement ratio, the amount of air entrainment, and the type of aggregate.

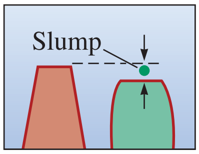


Figure 18-8
The slump test, in which deformation of a concrete shape under its own weight is measured, is used to describe the workability of concrete mix.

Water-Cement Ratio

The ratio of water to cement affects the behavior of concrete in several ways:

1. A minimum amount of water must be added to the cement to ensure that all of it undergoes the hydration reaction. Too little water therefore causes low strength. Normally, however, other factors such as workability place the lower limit on the water–cement ratio.
2. A high water–cement ratio improves the **workability** of concrete—that is, how easily the concrete slurry can fill all of the space in the form. Air pockets or interconnected porosity caused by poor workability reduce the strength and durability of the concrete structure. Workability can be measured by the *slump test*. For example, a wet concrete shape 30 cm tall is produced (Figure 18-8) and is permitted to stand under its own weight. After some period of time, the shape deforms. The reduction in height of the form is the **slump**. A minimum water–cement ratio of about 0.4 (by weight) is usually required for workability. A larger slump, caused by a higher water–cement ratio, indicates greater workability. Slumps of 2.5 to 15 cm are typical; high slumps are needed for pouring narrow or complex forms, while low slumps may be satisfactory for large structures such as dams.
3. Increasing the water–cement ratio beyond the minimum required for workability decreases the compressive strength of the concrete. This strength is usually measured by determining the stress required to crush a concrete cylinder 15 cm in diameter and 30 cm tall. Figure 18-9 shows the effect of the water–cement ratio on concrete's strength.
4. High water–cement ratios increase the shrinkage of concrete during curing, creating a danger of cracking.

Because of the different effects of the water–cement ratio, a compromise between strength, workability, and shrinkage may be necessary. A weight ratio of 0.45 to 0.55 is typical. To maintain good workability, organic plasticizers may be added to the mix with little effect on strength.

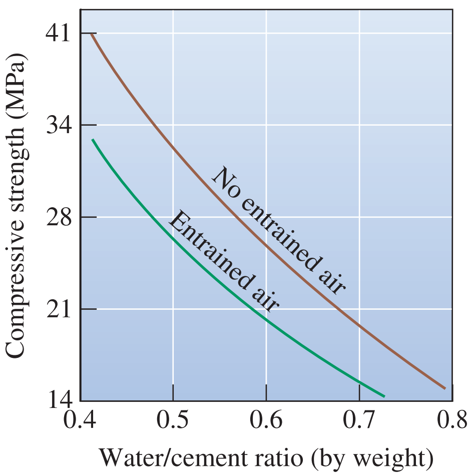


Figure 18-9
The effect of the water–cement ratio and entrained air on the 28-day compressive strength of concrete.

Air-Entrained Concrete Almost always, a small amount of air is entrained into the concrete during pouring. For coarse aggregate, such as 4 cm rock, 1% by volume of the concrete may be air. For finer aggregate, such as 1.3 cm gravel, 2.5% air may be trapped.

We sometimes intentionally entrain air into concrete—sometimes as much as 8% for fine gravel. The entrained air improves workability of the concrete and helps minimize problems with shrinkage and freeze–thaw conditions. Air-entrained concrete has a lower strength, however. (See Figure 18-9.)

Type and Amount of Aggregate The size of the aggregate affects the concrete mix. Figure 18-10 shows the amount of water per cubic yard of concrete required to produce the desired slump, or workability; more water is required for smaller aggregates. Figure 18-11 shows the amount of aggregate that should be present in the concrete mix. The volume ratio of aggregate in the concrete is based on the bulk density of the aggregate, which is about 60% of the true density shown in Table 18-6.

The examples that follow show how to calculate the contents for a concrete mixture.

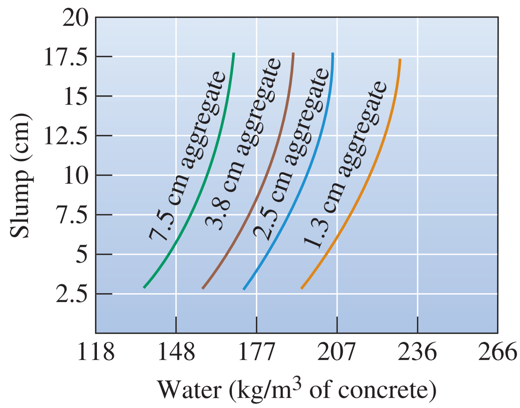


Figure 18-10
The amount of water per cubic yard of concrete required to give the desired workability (or slump) depends on the size of the coarse aggregate.

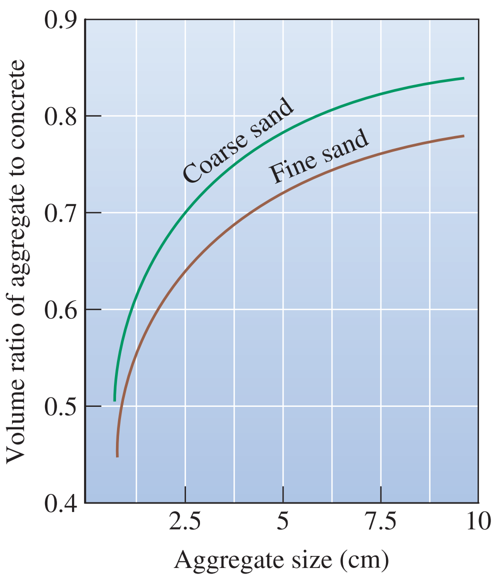


Figure 18-11
The volume ratio of aggregate to concrete depends on the sand and aggregate sizes. Note that the volume ratio uses the bulk density of the aggregate—about 60% of the true density.

Example 18-2 *Composition of Concrete*

Determine the amounts of water, cement, sand, and aggregate in 4 cubic meters of concrete, assuming that we want to obtain a water/cement ratio of 0.4 (by weight) and that the cement/sand/aggregate ratio is 1:2.5:4 (by weight). A "normal" aggregate will be used, containing 1% water, and the sand contains 4% water. Assume that no air is entrained into the concrete.

SOLUTION

One method by which we can calculate the concrete mix is to first determine the volume of each constituent based on one sack (42.6 kg) of cement. We should remember that after the concrete is poured, there are no void spaces between the various constituents; therefore, we need to consider the true density—not the bulk density—of the constituents in our calculations.

For each sack of cement we use, the volume of materials required is

$$\text{Cement} = \frac{42.6\ \text{kg/sack}}{3\ \text{g/cm}^3} = 0.014\ \text{m}^3$$

$$\text{Sand} = \frac{2.5 \times 42.6\ \text{kg cement}}{2.6\ \text{g/cm}^3} = 0.041\ \text{m}^3$$

$$\text{Gravel} = \frac{4 \times 42.6\ \text{kg cement}}{2.7\ \text{g/cm}^3} = 0.063\ \text{m}^3$$

$$\text{Water} = \frac{0.4 \times 42.6\ \text{kg cement}}{1\ \text{g/cm}^3} = 0.017\ \text{m}^3$$

$$\text{Total volume of concrete} = 0.135\ \text{m}^3\text{/sack of cement}$$

Therefore, in 4 m^3 (or 135 ft^3), we need

$$\text{Cement} = \frac{4\ \text{m}^3}{0.135\ \text{m}^3\text{/sack}} = 30\ \text{sacks}$$

$$\text{Sand} = (30\ \text{sacks})(42.6\ \text{kg/sack})(2.5\ \text{sand/cement}) = 3195\ \text{kg}$$

$$\text{Gravel} = (30\ \text{sacks})(42.6\ \text{kg/sack})(4\ \text{gravel/cement}) = 5112\ \text{kg}$$

$$\text{Water} = (30\ \text{sacks})(42.6\ \text{kg/sack})(0.4\ \text{water/cement}) = 511\ \text{kg}$$

The sand contains 4% water and the gravel contains 1% water. To obtain the weight of the *wet* sand and gravel, we must adjust for the water content of each:

$$\text{Sand} = (3195\ \text{kg dry})/0.96 = 3323\ \text{kg and water} = 128\ \text{kg}$$

$$\text{Gravel} = (5112\ \text{kg dry})/0.99 = 5163\ \text{kg and water} = 51\ \text{kg}$$

Therefore, we actually only need to add:

$$\text{Water} = 511\ \text{kg} - 128\ \text{kg} - 51\ \text{kg} = 332\ \text{kg}$$

$$= \frac{(332\ \text{kg})}{1\ \text{g/cm}^3} = 332{,}000\ \text{cm}^3 = 332\ \text{liters}$$

Accordingly, we recommend that 30 sacks of cement, 3323 kg of sand, and 5163 kg of gravel be combined with 332 liters of water.

Example 18-3 Design of a Concrete Mix for a Retaining Wall

Design a concrete mix that will provide a 28-day compressive strength of 28 MPa in a concrete intended for producing a 13 cm-thick retaining wall 180 cm high. We expect to have about 2% air entrained in the concrete, although we will not intentionally entrain air. The aggregate contains 1% moisture, and we have only coarse sand containing 5% moisture available.

SOLUTION

Some workability of the concrete is needed to ensure that the form will fill properly with the concrete. A slump of 8 cm might be appropriate for such an application. The wall thickness is 13 cm. To help minimize cost, we would use a large aggregate. A 2.5 cm diameter aggregate size would be appropriate (about 1/5 of the wall thickness).

To obtain the desired workability of the concrete using 2.5 cm aggregate, we should use about 189 kg of water per cubic meter (Figure 18-10).

To obtain the 28 MPa compressive strength after 28 days (assuming no intentional entrained air), we need a water–cement weight ratio of 0.57 (Figure 18-9).

Consequently, the weight of cement required per cubic meter of concrete is (189 kg water/0.57 water–cement) = 332 kg cement.

Because our aggregate size is 2.5 cm and we have only coarse sand available, the volume ratio of the aggregate to the concrete is 0.7 (Figure 18-11). Thus, the amount of aggregate required per meter of concrete is 0.7 m^3; however, this amount is in terms of the bulk density of the aggregate. Because the bulk density is about 60% of the true density, the actual volume occupied by the aggregate in the concrete is $0.7\ m^3 \times 0.6 = 0.42\ m^3$.

Let's determine the volume of each constituent per cubic meter (27 ft^3) of concrete in order to calculate the amount of sand required:

$$\begin{aligned}
\text{Water} &= 189\,\text{kg}/(1\,\text{g/cm}^3) = 0.19\,\text{m}^3 \\
\text{Cement} &= 332\,\text{kg}/(3\,\text{g/cm}^3) = 0.11\,\text{m}^3 \\
\text{Aggregate} &= 0.42\,\text{m}^3 \\
\text{Air} &= 0.02 \times 1\,\text{m}^3 = 0.02\,\text{m}^3 \\
\text{Sand} &= 1 - 0.19 - 0.11 - 0.42 - 0.02 = 0.26\,\text{m}^3
\end{aligned}$$

Or converting to other units, assuming that the aggregate and sand are dry:

$$\begin{aligned}
\text{Water} &= 0.19\,\text{m}^3 \times \frac{1\ \text{liter}}{1000\ \text{cc}} = 190\ \text{liter}s \\
\text{Cement} &= 332\,\text{kg}/(42.6\,\text{kg/sack}) = 8\,\text{sacks} \\
\text{Aggregate} &= 0.42\,\text{m}^3 \times 2.7\,\text{g/cm}^3 = 1134\,\text{kg} \\
\text{Sand} &= 0.26\,\text{m}^3 \times 2.6\,\text{g/m}^3 = 676\,\text{kg}
\end{aligned}$$

The aggregate and the sand are wet. Thus, the actual amounts of aggregate and sand needed are

$$\begin{aligned}
\text{Aggregate} &= 1134/0.99 = 1145\,\text{kg}\,(11\,\text{kg water}) \\
\text{Sand} &= 676\,\text{kg}/0.95 = 710\,\text{kg}\,(34\,\text{kg water})
\end{aligned}$$

The actual amount of water needed is

$$\text{Water} = 190 \text{ liters} - \frac{(11 \text{ kg} + 34 \text{ kg})(1 \text{ liter}/1000 \text{ cc})}{1 \text{ g/cm}^3} = 145 \text{ liters}$$

Thus, for each cubic yard of concrete, we will combine eight sacks of cement, 1145 kg of aggregate, 710 kg of sand, and 145 liters of water. This should give us a slump of 8 cm (the desired workability) and a compressive strength of 28 MPa after 28 days.

18-8 Reinforced and Prestressed Concrete

Concrete, like other ceramic-based materials, develops good compressive strength. Due to the porosity and interfaces present in the brittle structure, however, it has very poor tensile properties. Several methods are used to improve the load-bearing capability of concrete in tension.

Reinforced Concrete Steel rods (known as rebar), wires, or mesh are frequently introduced into concrete to provide improvement in resisting tensile and bending forces. The tensile stresses are transferred from the concrete to the steel, which has good tensile properties. Polymer fibers, which are less likely to corrode, also can be used as reinforcement. Under flexural stresses, the steel supports the part that is in tension; the part that is under compression is supported by the concrete.

Prestressed Concrete Instead of simply being laid as reinforcing rods in a form, the steel initially can be pulled in tension between an anchor and a jack, thus remaining under tension during the pouring and curing of the concrete. After the concrete sets, the tension on the steel is released. The steel then tries to relax from its stretched condition, but the restraint caused by the surrounding concrete places the concrete in compression. Now higher tensile and bending stresses can be applied to the concrete because of the compressive residual stresses introduced by the pretensioned steel. In order to permit the external tension to be removed in a timely manner, the early-setting Type III cements are often used for these applications.

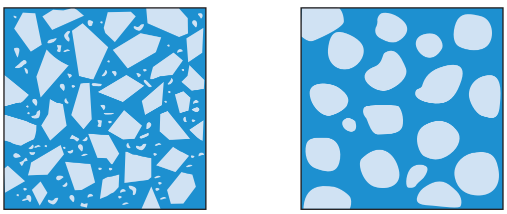
Poststressed Concrete An alternate method of placing concrete under compression is to place hollow tubes in the concrete before pouring. After the concrete cures, steel rods or cables running through the tubes then can be pulled in tension, acting against the concrete. As the rods are placed in tension, the concrete is placed in compression. The rods or cables then are secured permanently in their stretched condition.

18-9 Asphalt

Asphalt is a composite of aggregate and **bitumen**, which is a thermoplastic polymer most frequently obtained from petroleum. Asphalt is an important material for paving roads. The properties of the asphalt are determined by the characteristics of the aggregate and binder, their relative amounts, and additives.

The aggregate, as in concrete, should be clean and angular and should have a distribution of grain sizes to provide a high packing factor and good mechanical interlocking between the aggregate grains (Figure 18-12). The binder, composed of thermoplastic chains, bonds the aggregate particles. The binder has a relatively narrow useful temperature range, being brittle at sub-zero temperatures and beginning to melt at relatively low temperatures. Additives such as gasoline or kerosene can be used to modify the binder, permitting it to liquefy more easily during mixing and causing the asphalt to cure more rapidly after application.

The ratio of binder to aggregate is important. Just enough binder should be added so that the aggregate particles touch, but voids are minimized. Excess binder permits viscous deformation of the asphalt under load. Approximately 5 to 10% bitumen is present in a typical asphalt. Some void space is also required—usually, about 2 to 5%. When the asphalt is compressed, the binder can squeeze into voids, rather than be squeezed from the surface of the asphalt and lost. Too much void space, however, permits water to enter the structure; this increases the rate of deterioration of the asphalt and may embrittle the binder. Emulsions of asphalt are used for sealing driveways. The aggregate for asphalt is typically sand and fine gravel; however, there is some interest in using recycled glass products as the aggregate. **Glasphalt** provides a useful application for crushed glass. Similarly, there are also applications for materials developed using asphalt and shredded rubber tires.



(a) **(b)**

Figure 18-12
The ideal structure of asphalt (a) compared with the undesirable structure (b) in which round grains, a narrow distribution of grains, and excess binder all reduce the strength of the final material.

Summary

- Construction materials play a vital role in the infrastructure of any nation. Concrete, wood, asphalt, glasses, composites, and steels are some of the most commonly encountered materials.
- Advanced materials used to make sensors and actuators also play an increasingly important role in monitoring the structural health of buildings and bridges. There are also new coatings and thin films on glasses that have contributed to more energy-efficient buildings.
- Wood is a natural fiber-reinforced polymer composite material. Cellulose fibers constitute aligned cells that provide excellent reinforcement in longitudinal directions in wood, but give poor strength and stiffness in directions perpendicular to the cells and fibers. The properties of wood therefore are highly anisotropic and depend on the species of the tree and the amount of moisture present in the wood. Wood has good tensile strength but poor compressive strength.
- Concrete is a particulate composite. In concrete, ceramic particles such as sand and gravel are used as filler in a ceramic-cement matrix. The water–cement ratio is a particularly important factor governing the behavior of the concrete. This behavior can be modified by entraining air and by varying the composition of the cement and aggregate materials. Concrete has good compressive strength but poor tensile strength.
- Asphalt also is a particulate composite, using the same type of aggregates as in concrete, but with an organic, polymer binder.

Glossary

Aggregate A combination of gravel, sand, crushed stones, or slag.

Bitumen The organic binder, composed of low melting point polymers and oils, for asphalt.

Cambium The layer of growing cells in wood.

Cellulose A naturally occurring polymer fiber that is the major constituent of wood. Cellulose has a high degree of polymerization.

Cements Inorganic materials that set and harden after being mixed into a paste using water.

Concrete A composite material that consists of a binding medium in which particles of aggregate are dispersed.

Extractives Impurities in wood.

Glasphalt Asphalt in which the aggregate includes recycled glass.

Heartwood The center of a tree comprised of dead cells, which provides mechanical support to a tree.

Hemicellulose A naturally occurring polymer fiber that is an important constituent of wood. It has a low degree of polymerization.

Hydraulic cement A cement that sets and hardens under water.

Lignin The polymer cement in wood that bonds the cellulose fibers in the wood cells.

Microfibril Bundles of cellulose and other polymer chains that serve as the fiber reinforcement in wood.

Mortar A mortar is made by mixing cement, water, air, and fine aggregates. Concrete contains all of the ingredients of the mortar and coarse aggregates.

Nonhydraulic Cement Cements that cannot harden under water and require air for hardening.

Plies The individual sheet of wood veneer from which plywood is constructed.

Portland cement A hydraulic cement made from calcium silicates; the approximate composition is CaO (~60–65%), SiO_2 (~20–25%), and iron oxide and alumina (~7 to 12%).

Sapwood Hollow, living cells in wood that store nutrients and conduct water.

Slump The decrease in height of a standard concrete form when the concrete settles under its own weight.

Workability The ease with which a concrete slurry fills all of the space in a form.

Section 18-1 The Structure of Wood

Section 18-2 Moisture Content and Density of Wood

Section 18-3 Mechanical Properties of Wood

Section 18-4 Expansion and Contraction of Wood

Section 18-5 Plywood

18-1 Table 18-1 lists the densities for typical woods. Calculate the densities of the woods after they are completely dried and at 100% water content.

18-2 A sample of wood with the dimensions 8 cm × 10 cm × 30 cm has a dry density of 0.35 g/cm^3.
(a) Calculate the number of gallons of water that must be absorbed by the sample to contain 120% water.
(b) Calculate the density after the wood absorbs this amount of water.

18-3 The density of a sample of oak is 0.90 g/cm^3. Calculate
(a) the density of completely dry oak and
(b) the percent water in the original sample.

18-4 A green wood with a density of 0.82 g/cm^3 contains 150% water. The compressive strength of this wood is 27 MPa. After several days of drying, the compressive strength increases to 41 MPa. What is the water content and density of the dried wood? Refer to Figure 18-4.

18-5 Boards of oak 0.5 cm thick, 1 m long, and 0.25 m wide are used as flooring for a 10 m × 10 m area. If the floor was laid at a moisture content of 25% and the expected moisture could be as high as 45%, determine the dimensional change in the floor parallel to and perpendicular to the length of the boards. The boards were cut from logs with a tangential-longitudinal cut.

18-6 Boards of maple 3 cm thick, 15 cm wide, and 40 cm long are used as the flooring for a 18 m × 18 m hall. The boards were cut from logs with a tangential-longitudinal cut. The floor is laid when the boards have a moisture content of 12%. After some particularly humid days, the moisture content in the boards increases to 45%. Determine the dimensional change in the flooring parallel to the boards and perpendicular to the boards. What will happen to the floor? How can this problem be corrected?

18-7 A wall 9 m long is built using radial-longitudinal cuts of 13 cm wide pine with the boards arranged in a vertical fashion. The wood contains a moisture content of 55% when the wall is built;

however, the humidity level in the room is maintained to give 45% moisture in the wood. Determine the dimensional changes in the wood boards, and estimate the size of the gaps that will be produced as a consequence of these changes.

Section 18-6 Concrete Materials

Section 18-7 Properties of Concrete

Section 18-8 Reinforced and Prestressed Concrete

Section 18-9 Asphalt

18-8 Determine the amounts of water, cement, and sand in 10 m^3 of concrete if the cement–sand–aggregate ratio is 1:2.5:4.5 and the water–cement ratio is 0.4. Assume that no air is entrained into the concrete. The sand used for this mixture contains 4 wt% water, and the aggregate contains 2 wt% water.

18-9 Calculate the amount of cement, sand, aggregate, and water needed to create a concrete mix with a 28-day compressive strength of 34 MPa for a 10 m × 10 m × 0.25 m structure given the following conditions: allowed slump = 10 cm and only 3.8 cm aggregate with 2% moisture and coarse sand with 4% moisture are available for this project. Assume no air entrainment in your calculations.

18-10 We have been asked to prepare 80 m^3 of normal concrete using a volume ratio of cement–sand–coarse aggregate of 1:2:4. The water–cement ratio (by weight) is to be 0.5. The sand contains 6 wt% water, and the coarse aggregate contains 3 wt% water. No entrained air is expected.

(a) Determine the number of sacks of cement that must be ordered, the kilograms of sand and aggregate required, and the amount of water needed.

(b) Calculate the total weight of the concrete per cubic meter.

(c) What is the weight ratio of cement–sand–coarse aggregate?

18-11 We plan to prepare 10 m^3 of concrete using a 1:2.5:4.5 weight ratio of cement-sand-coarse aggregate. The water–cement ratio (by weight) is 0.45. The sand contains 3 wt% water; the coarse aggregate contains 2 wt% water; and 5% entrained air is expected. Determine the number of sacks of cement, kilograms of sand and coarse aggregate, and liters of water required.

Design Problems

18-12 A wooden structure is functioning in an environment controlled at 65% humidity. Design a wood support column that is to hold a compressive load of 90,000 N. The distance from the top to the bottom of the column should be 240 ± 0.63 cm when the load is applied.

18-13 Design a wood floor that will be 15 m by 50 ft and will be in an environment in which humidity changes will cause a fluctuation of plus or minus 5% water in the wood. We want to minimize any buckling or gap formation in the floor.

18-14 We would like to produce a concrete that is suitable for use in building a large structure in a sulfate environment. For these situations, the maximum water–cement ratio should be 0.45 (by weight). The compressive strength of the concrete after 28 days should be at least 28 MPa. We have an available coarse aggregate containing 2% moisture in a variety of sizes, and both fine and coarse sand containing 4% moisture. Design a concrete that will be suitable for this application.

18-15 We would like to produce a concrete sculpture. The sculpture will be as thin as 8 cm in some areas and should be light in weight, but it must have a 28-day compressive strength of at least 14 MPa. Our available aggregate contains 1% moisture, and our sands contain 5% moisture. Design a concrete that will be suitable for this application.

18-16 The binder used in producing asphalt has a density of about 1.3 g/cm^3. Design an asphalt, including the weight and volumes of each constituent, that might be suitable for use as pavement. Assume that the sands and aggregates are the same as those for a normal concrete.

18-17 *Concrete Canoe Design*. Describe what novel materials can be used to make a concrete canoe.

Knovel® Problems

K18-1 What is the difference in lignin content between hardwood and softwood species? What is the chemical structure of lignin?

K18-2 The equilibrium moisture content of wood is the moisture content at which the wood is neither gaining nor losing moisture. What is the moisture content of wood at 21°C with a relative humidity of 50%?

K18-3 What measures are used to control cracking in reinforced concrete?