SECTION FOUR
BUILDING MATERIALS

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This section describes the basic materials used in building construction and discusses their common applications. As the world's population increases and consumes more of the natural resources, it is incumbent upon the civil engineer to use building materials that contribute to sustaining development instead of satisfying only the short-term need. Material selection should incorporate an evaluation of the amount of energy required to produce and deliver the material to the building site. This concept of ''embodied energy'' is evolving and variable. As an example, in the Pacific Northwest lumber would have an ''embodied energy'' of 1, but in the arid Southwest transportation raises the value several points. Examples of other materials are concrete (2–3), steel (4–6), and aluminum (80). For discussion purposes, materials used in similar applications are grouped and discussed in sequence, for example, masonry materials, wood, metals, plastics, etc.

CEMENTITIOUS MATERIALS

Cementitious materials include the many products that are mixed with either water or some other liquid or both to form a cementing paste that may be formed or molded while plastic but will set into a rigid shape. When sand is added to the paste, mortar is formed. A combination of coarse and fine aggregate (sand) added to the paste forms concrete.

4.1 TYPES OF CEMENTITIOUS MATERIALS

There are many varieties of cements and numerous ways of classification. One of the simplest classifications is by the chemical constituent that is responsible for the setting or hardening of the cement. On this basis, the silicate and aluminate cements, wherein the setting agents are calcium silicates and aluminates, constitute the most important group of modern cements. Included in this group are the portland, aluminous, and natural cements.

Limes, wherein the hardening is due to the conversion of hydroxides to carbonates, were formerly widely used as the sole cementitious material, but their slow setting and hardening are not compatible with modern requirements. Hence, their principal function today is to plasticize the otherwise harsh cements and add resilience to mortars and stuccoes. Use of limes is beneficial in that their slow setting promotes healing, the recementing of hairline cracks.

Another class of cements is composed of calcined gypsum and its related products. The gypsum cements are widely used in interior plaster and for fabrication of boards and blocks; but the solubility of gypsum prevents its use in construction exposed to any but extremely dry climates.

Oxychloride cements constitute a class of specialty cements of unusual properties. Their cost prohibits their general use in competition with the cheaper cements; but for special uses, such as the production of sparkproof floors, they cannot be equaled.

Masonry cements or mortar cements are widely used because of their convenience. While they are, in general, mixtures of one of more of the above-mentioned cements with some admixtures, they deserve special consideration because of their economies.

Other cementitious materials, such as polymers, fly ash, and silica fume, may be used as a cement replacement in concrete. Polymers are plastics with long-chain molecules. Concretes made with them have many qualities much superior to those of ordinary concrete.

Silica fume, also known as microsilica, is a waste product of electric-arc furnaces. The silica reacts with limes in concrete to form a cementitious material. A fume particle has a diameter only 1% of that of a cement particle.

4.2 PORTLAND CEMENTS

Portland cement, the most common of the modern cements, is made by carefully blending selected raw materials to produce a finished material meeting the requirements of ASTM C150 for one of eight specific cement types. Four major compounds [lime (CaO), iron (Fe_2O_3), silica (SiO_2), and alumina (Al_2O_3)] and two minor compounds [gypsum ($CaSO_4 \cdot 2H_2O$) and magnesia (MgO)] constitute the raw materials. The calcareous (CaO) materials typically come from limestone, calcite, marl, or shale. The argillaceous (SiO_2 and Al_2O_3) materials are derived from clay, shale, and sand. The materials used for the manufacture of any specific cement are dependent on the manufacturing plant's location and availability of raw materials. Portland cement can be made of a wide variety of industrial by-products.

In the manufacture of cement, the raw materials are first mined and then ground to a powder before blending in predetermined proportions. The blend is fed into the upper end of a rotary kiln heated to 2600 to 3000°F by burning oil, gas, or powdered coal. Because cement production is an energy-intensive process, reheaters and the use of alternative fuel sources, such as old tires, are used to reduce the fuel cost. (Burning tires provide heat to produce the clinker and the steel belts provide the iron constituent.) Exposure to the elevated temperature chemically fuses the raw materials together into hard nodules called cement clinker. After cooling, the clinker is passed through a ball mill and ground to a fineness where essentially all of it will pass a No. 200 sieve (75 μm). During the grinding, gypsum is added in small amounts to control the temperature and regulate the cement setting time. The material that exits the ball mill is portland cement. It is normally sold in bags containing 94 lb of cement.

Concrete, the most common use for portland cement, is a complex material consisting of portland cement, aggregates, water, and possibly chemical and mineral admixtures. Only rarely is portland cement used alone, such as for a cement slurry for filling well holes or for a fine grout. Therefore, it is important to examine the relationship between the various portland cement properties and their potential effect upon the finished concrete. Portland cement concrete is generally selected for structural use because of its strength and durability. Strength is easily measured and can be used as a general directly proportional indicator of overall durability. Specific durability cannot be easily measured but can be specified by controlling the cement chemistry and aggregate properties.

4.2.1 Specifications for Portland Cements

ASTM C150 defines requirements for eight types of portland cement. The pertinent chemical and physical properties are shown in Table 4.1. The chemical composition of portland cement is expressed in a cement-chemistry shorthand based on four phase compounds: tricalcium silicate (C_3S), dicalcium silicate (C_2S), tricalcium aluminate (C_3A), and tetracalcium aluminum ferrite (C_4AF). C_2S and C_3S are termed the calcium silicate hydrates (CSH).

Most cements will exceed the requirements shown in Table 4.1 by a comfortable margin. Note that the required compressive strengths are minimums. Almost without exception, every portland cement will readily exceed these minimum values. However, a caution must be attached to compressive strengths that significantly exceed the minimum values. While there is not a one-to-one correlation between a cement cube strength and the strength of concrete made with that cement (5000-psi cement does not equate to 5000-psi concrete), variations in cube strengths will be reflected in the tested concrete strength. It is imperative that, as the designed concrete strength reaches 5000 psi and greater, the cement cube strength be rigorously monitored. Any lowering of the running average will have a negative effect on the strength of concrete if the concrete mix design is not altered.

The basic types of portland cement covered by ASTM C150 are as follows:

Type I, general-purpose cement, is the one commonly used for many structural purposes. Chemical requirements for this type of cement are limited to magnesia and sulfur-trioxide contents and loss on ignition, since the cement is adequately defined by its physical characteristics.

Type II is a modified cement for use in general concrete where a moderate exposure to sulfate attack may be anticipated or where a moderate heat of hydration is required. These characteristics are attained by placing limitations on the C_3S and C_3A content of the cement. Type II cement gains strength a little more slowly than Type I but ultimately will achieve equal strength. It is generally available in most sections of the country and is preferred by some engineers over Type I for general construction. Type II cement may also be specified as a low-alkali cement for use where alkali reactive aggregates are present. To do so requires that optional chemical requirements (Table 4.2) be included in the purchase order. Type II low-alkali cement is commonly specified in California.

Type III cement attains high early strength. In 7 days, strength of concrete made with it is practically equal to that made with Type I or Type II cement at 28 days. This high early strength is attained by finer grinding (although no minimum is placed on the fineness by specification) and by increasing the C_3S and C_3A content

TABLE 4.1 Chemical and Physical Requirements for Portland Cement*

Type:	I and IA	II and IIA	III and IIIA	IV	V
Name:	General-purpose	Modified	High early	Low-heat	Sulfate-resisting
C_3S, max %				35	
C_2S, min %				40	
C_3A, max %		8	15	7	5
SiO_2, min %		20			
Al_2O_3, max %		6			
Fe_2O_3, max %		6		6.5	
MgO, max %	6	6	6	6	6
SO_3, max %:					
When $C_3A \leq 8\%$	3	3	3.5	2.3	2.3
When $C_3A > 8\%$	3.5		4.5		
$C_4AF + 2(C_3A)$, max %					25
Fineness, specific surface, m^2/kg	160	160		160	160
Average min, by turbidimeter					
Average min, by air permeability test	280	280		280	280
Compressive strength, psi, mortar cubes of 1 part cement and 2.75 parts graded standard sand after:					
1 day min			1800		
Standard					
Air-entraining			1450		
3 days min	1800	1500	3500		1200
Standard					
Air-entraining	1450	1200	2800		
7 days min	2800	2500		1000	2200
Standard					
Air-entraining	2250	2000			
28 days min				2500	3000
Standard					

*Based on requirements in "Standard Specification for Portland Cement," ASTM C150. See current edition of C150 for exceptions, alternatives, and changes in requirements.

of the cement. Type III cement, however, has high heat evolution and therefore should not be used in large masses. Because of the higher C_3A content, Type III cement also has poor sulfate resistance. Type III cement is not always available from building materials dealers' stocks but may be obtained by them from the cement manufacturer on short notice. Ready-mix concrete suppliers generally do not stock Type III cement because its shorter set time makes it more volatile to transport and discharge, especially in hot weather.

Type IV is a low-heat cement that has been developed for mass concrete construction. Normal Type I cement, if used in large masses that cannot lose heat by radiation, will liberate enough heat during the hydration of the cement to raise the temperature of the concrete as much as 50 or 60°F. This results in a relatively large increase in dimensions while the concrete is still soft and plastic. Later, as the concrete cools are hardening, shrinkage causes cracks to develop, weakening the

TABLE 4.2 Optional Chemical Requirements for Portland Cement*

Cement type	I and IA	II and IIA	III and IIIA	IV	V
Tricalcium aluminate (C_3A), max %					
For moderate sulfate resistance			8		
For high sulfate resistance			5		
Sum of tricalcium silicate and tricalcium aluminate, max %†		58			
Alkalies ($Na_2O + 0.658K_2O$), max %‡	0.60	0.60	0.60	0.60	0.60

*These optional requirements apply only if specifically requested. Availability should be verified.

†For use when moderate heat of hydration is required.

‡Low-alkali cement. This limit may be specified when cement is to be used in concrete with aggregates that may be deleteriously reactive. See "Standard Specification for Concrete Aggregates," ASTM C33.

concrete and affording points of attack for aggressive solutions. The potential-phase compounds that make the largest contribution to the heat of hydration are C_3S and C_3A; so the amounts of these are permitted to be present are limited. Since these compounds also produce the early strength of cement, the limitation results in a cement that gains strength relatively slowly. This is of little importance, however, in the mass concrete for which this type of cement is designed.

Type V is a portland cement intended for use when high sulfate resistance is required. Its resistance to sulfate attack is attained through the limitation on the C_3A content. It is particularly suitable for structures subject to attack by liquors containing sulfates, such as liquids in wastewater treatment plants, seawaters, and some other natural waters.

Both Type IV and Type V cements are specialty cements. They are not normally available from dealer's stock but are usually obtainable for use on a large job if arrangements are made with the cement manufacturer in advance.

4.2.2 Air-Entraining Portland Cements

For use in the manufacturer of air-entraining concrete, agents may be added to the cement by the manufacturer, thereby producing air-entraining portland cements ("Air-Entraining Additions for Use in the Manufacture of Air-Entraining Portland Cement," ASTM C226). These cements are available as Types IA, IIA, and IIIA.

4.3 ALUMINOUS CEMENTS

These are prepared by fusing a mixture of aluminous and calcareous materials (usually bauxite and limestone) and grinding the resultant product to a fine powder. These cements are characterized by their rapid-hardening properties and the high strength developed at early ages. Table 4.3 shows the relative strengths of 4-in cubes of 1:2:4 concrete made with normal portland, high-early-strength portland, and aluminous cements.

Since a large amount of heat is liberated with rapidly by aluminous cement during hydration, care must be taken not to use the cement in places where this

TABLE 4.3 Relative Strengths of Concrete Made from Portland and Aluminous Cements*

	Compressive strength, psi		
Days	Normal portland	High-early portland	Aluminous
1	460	790	5710
3	1640	2260	7330
7	2680	3300	7670
28	4150	4920	8520
56	4570	5410	8950

*Adapted from F. M. Lea, ‘‘Chemistry of Cement and Concrete,’’ St. Martin’s Press, Inc., New York.

heat cannot be dissipated. It is usually not desirable to place aluminous-cement concretes in lifts of over 12 in; otherwise the temperature rise may cause serious weakening of the concrete.

Aluminous cements are much more resistant to the action of sulfate waters than are portland cements. They also appear to be much more resistant to attack by water containing aggressive carbon dioxide or weak mineral acids than the silicate cements. Their principal use is in concretes where advantage may be taken of their very high early strength or of their sulfate resistance, and where the extra cost of the cement is not an important factor.

Another use of aluminous cements is in combination with firebrick to make refractory concrete. As temperatures are increased, dehydration of the hydration products occurs. Ultimately, these compounds create a ceramic bond with the aggregates.

4.4 NATURAL CEMENTS

Natural cements are formed by calcining a naturally occurring mixture of calcareous and argillaceous substances at a temperature below that at which sintering takes place. The ‘‘Specification for Natural Cement,’’ ASTM C10, requires that the temperature be no higher than necessary to drive off the carbonic acid gas. Since natural cements are derived from naturally occurring materials and no particular effort is made to adjust the composition, both the composition and properties vary rather widely. Some natural cements may be almost the equivalent of portland cement in properties; others are much weaker. Natural cements are principally used in masonry mortars and as an admixture in portland-cement concretes.

4.5 LIMES

These are made principally of calcium oxide (CaO), occurring naturally in limestone, marble, chalk, coral, and shell. For building purposes, they are used chiefly in mortars.

4.5.1 Hydraulic Limes

These are made by calcining a limestone containing silica and alumina to a temperature short of incipient fusion so as to form sufficient free lime to permit hydration and at the same time leave unhydrated sufficient calcium silicates to give the dry powder its hydraulic properties (see ''Specification for Hydraulic Hydrated Lime for Structural Purposes,'' ASTM C141).

Because of the low silicate and high lime contents, hydraulic limes are relatively weak. They find their principal use in masonry mortars. A hydraulic lime with more than 10% silica will set under water.

4.5.2 Quicklimes

When limestone is heated to a temperature in excess of 1700°F, the carbon dioxide content is driven off and the remaining solid product is quicklime. It consists essentially of calcium and magnesium oxides plus impurities such as silica, iron, and aluminum oxides. The impurities are usually limited to less than 5%. If they exceed 10%, the product may be a hydraulic lime.

Two classes of quicklime are recognized, high-calcium and dolomitic. A high-calcium quicklime usually contains less than 5% magnesium oxide. A dolomitic quicklime usually contains from 35 to 40% magnesium oxide. A few quicklimes are found that contain 5 to 35% magnesium oxide and are called magnesian limes.

The outstanding characteristic of quicklime is its ability to slake with water. When quicklime is mixed with from two to three times its weight of water, a chemical reaction takes place. The calcium oxide combines with water to form calcium hydroxide, and sufficient heat is evolved to bring the entire mass to a boil. The resulting product is a suspension of finely divided calcium hydroxide (and magnesium hydroxide or oxide if dolomitic lime is used) in water. On cooling, the semifluid mass stiffens to a putty of such consistency that it may be shoveled or carried in a hod. This slaked quicklime putty, when cooled and preferably screened, is the material used in construction. Quicklime should always be thoroughly slaked.

The yield of putty will vary, depending on the type of quicklime, its degree of burning, and slaking conditions, and will usually be from 70 to 100 ft^3 of putty per ton of quicklime. The principal use of the putty is in masonry mortars, where it is particularly valuable because of the high degree of plasticity or workability it imparts to the mortar. It is used at times as an admixture in concrete to improve workability. It also is used in some localities as finish-coat plaster where full advantage may be taken of its high plasticity.

4.5.3 Mason's Hydrated Lime

Hydrated limes are prepared from quicklimes by addition of a limited amount of water. After hydration ceases to evolve heat, the resulting product is a fine, dry powder. It is then classified by air-classification methods to remove undesirable oversize particles and packaged in 50-lb sacks. It is always a factory-made product, whereas quicklime putty is almost always a job-slaked product.

Mason's hydrated limes are those hydrates suitable for use in mortars, base-coat plasters, and concrete. They necessarily follow the composition of the quicklime. High-calcium hydrates are composed primarily of calcium hydroxide. Normal dolomitic hydrates are composed of calcium hydroxide plus magnesium oxide.

Plasticity of mortars made from normal mason's hydrated limes (Type N) is fair. It is better than that attained with most cements, but not nearly so high as that of mortars made with an equivalent amount of slaked putty.

The normal process of hydration of a dolomitic quicklime at atmospheric pressure results in the hydration of the calcium fraction only, leaving the magnesium-oxide portion substantially unchanged chemically. When dolomitic quicklime is hydrated under pressure, the magnesium oxide is converted to magnesium hydroxide. This results in the so-called special hydrates (Type S), which not only have their magnesia contents substantially completely hydrated but also have a high degree of plasticity immediately on wetting with water. Mortars made from Type S hydrates are more workable than those made from Type N hydrates. In fact, Type S hydrates are nearly as workable as those made from slaked quicklime putties. The user of this type of hydrate may therefore have the convenience of a bagged product and a high degree of workability without having the trouble and possible hazard of slaking quicklime.

4.5.4 Finishing Hydrated Limes

Finishing hydrated limes are particularly suitable for use in the finishing coat of plaster. They are characterized by a high degree of whiteness and plasticity. Practically all finishing hydrated limes are produced in the Toledo district of Ohio from dolomitic limestone. The normal hydrate is composed of calcium hydroxide and magnesium oxide. When first wetted, it is no more plastic than Type N mason's hydrates. It differs from the latter, however, in that, on soaking overnight, the finishing hydrated lime develops a very high degree of plasticity, whereas the mason's hydrate shows relatively little improvements in plasticity on soaking.

4.6 LOW-TEMPERATURE GYPSUM DERIVATIVES

When gypsum rock ($CaSO_4 \cdot 2H_2O$) is heated to a relatively low temperature, about 130°C, three-fourths of the water of crystallization is driven off. The resulting product is known by various names such as hemihydrate, calcined gypsum, and first-settle stucco. Its common name, however, is **plaster of paris.** It is a fine powder, usually white. While it will set under water, it does not gain strength and ultimately, on continued water exposure, will disintegrate.

Plaster of paris, with set retarded or unretarded, is used as a molding plaster or as a gaging plaster. The molding plaster is used for preparing ornamental plaster objects. The gaging plaster is used for finishing hydrated lime to form the smooth white-coat finish on plaster walls. The unretarded plaster of paris is used by manufacturers to make gypsum block, tile, and gypsumboard (wallboard, lath, backerboard, coreboard, etc.).

When plaster of paris is retarded and mixed with fiber such as sisal, it is marketed under the name of hardwall plaster or cement plaster. (The latter name is misleading, since it does not contain any portland cement.) Hardwall plaster, mixed with water and with from two to three parts of sand by weight, is widely used for base-coat plastering. In some cases wood fiber is used in place of sand, making a ''wood-fibered'' plaster.

Special effects are obtained by combining hardwall plaster with the correct type of aggregate. With perlite or vermiculite aggregate, a lightweight plaster is obtained.

Gypsum plasters, in general, have a strong set, gain their full strength when dry, do not have abnormal volume changes, and have excellent fire-resistance characteristics. They are not well adapted, however, for use under continued damp conditions or intermittent wet conditions. See also Arts. 4.26 to 4.30.

4.7 OXYCHLORIDE CEMENTS

Lightly calcined magnesium oxide mixed with a solution of magnesium chloride forms a cement known as magnesium oxychloride cement, or **Sorel cement.** It is particularly useful in making flooring compositions in which it is mixed with colored aggregates. Floors made of oxychloride cement are sparkproof and are more resilient than floors of concrete.

Oxychloride cement has very strong bonding power and, because of its higher bonding power, may be used with greater quantities of aggregate than are possible with portland cement. Oxychloride cement also bonds well with wood and is used in making partition block or tile with wood shavings or sawdust as aggregate. It is moderately resistant to water but should not be used under continually wet conditions.

4.8 MASONRY CEMENTS

Masonry cements, or—as they are sometimes called—mortar cements, are intended to be mixed with sand and used for setting unit masonry, such as brick, tile, and stone. They may be any one of the hydraulic cements already discussed or mixtures of them in any proportion.

Many commercial masonry cements are mixtures of portland cement and pulverized limestone, often containing as much as 50 or 60% limestone. They are sold in bags containing from 70 to 80 lb, each bag nominally containing a cubic foot. Price per bag is commonly less than of portland cement, but because of the use of the lighter bag, cost per ton is higher than that of portland cement.

Since there are no limits on chemical content and physical requirements, masonry cement specifications are quite liberal. Some manufacturers vary the composition widely, depending on competition, weather conditions, or availability of materials. Resulting mortars may vary widely in properties.

4.9 FLY ASHES

Fly ash meeting the requirements of ASTM C618, ‘‘Specification for Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Portland Cement Concrete,’’ is generally used as a cementitious material as well as an admixture.

Natural pozzolans are derived from some diatomaceous earths, opaline cherts and shales, and other materials. While part of a common ASTM designation with fly ash, they are not as readily available as fly ashes and thus do not generate the same level of interest or research.

Fly ashes are produced by coal combustion, generally in an electrical generating station. The ash that would normally be released through the chimney is captured by various means, such as electrostatic precipitators. The fly ash may be sized prior to shipment to concrete suppliers.

All fly ashes possess pozzolanic properties, the ability to react with calcium hydroxide at ordinary temperatures to form compounds with cementitious properties. When cement is mixed with water, a chemical reaction (hydration) occurs. The product of this reaction is calcium silicate hydrate (CSH) and calcium hydroxide [$Ca(OH)_2$]. Fly ashes have high percentages of silicon dioxide (SiO_2). In the presence of moisture, the $Ca(OH)_2$ will react with the SiO_2 to form another CSH.

Type F ashes are the result of burning anthracite or bituminous coals and possess pozzolanic properties. They have been shown by research and practice to provide usually increased sulfate resistance and to reduce alkali-aggregate expansions. Type C fly ashes result from burning lignite or subbituminous coals. Because of the chemical properties of the coal, the Type C fly ashes have some cementitious properties in addition to their pozzolanic properties. Type C fly ashes may reduce the durability of concretes into which they are incorporated.

4.10 SILICA FUME (*MICROSILICA*)

Silica fume, or microsilica, is a condensed gas, the by-product of metallic silicon or ferrosilicon alloys produced by electric arc furnaces. (While both terms are correct, microsilica (MS) is a less confusing name.) The Canadian standard CAN/CSA-A23.5-M86, ''Supplementary Cementing Materials,'' limits amorphous SiO_2 to a maximum of 85% and oversize to 10%. Many MS contain more than 90% SiO_2.

MS has an average diameter of 0.1 to 0.2 μm, a particle size of about 1% that of portland cement. Because of this small size, it is not possible to utilize MS in its raw form. Manufacturers supply it either densified, in a slurry (with or without water-reducing admixtures), or pelletized. Either the densified or slurried MS can be utilized in concrete. The pelletized materials is densified to the point that it will not break down during mixing.

Because of its extremely small size, MS imparts several useful properties to concrete. It greatly increases long-term strength. It very efficiently reacts with the $Ca(OH)_2$ and creates a beneficial material in place of a waste product. MS is generally used in concrete with a design strength in excess of 12,000 psi. It provides increased sulfate resistance to concrete, and it significantly reduces the permeability of concrete. Also, its small size allows MS to physically plug microcracks and tiny openings.

AGGREGATES

Aggregate is a broad encompassing boulders, cobbles, crushed stone, gravel, air-cooled blast furnace slag, native and manufactured sands, and manufactured and natural lightweight aggregates. Aggregates may be further described by their respective sizes.

4.11 NORMAL-WEIGHT AGGREGATES

These typically have specific gravities between 2.0 and 3.0. They are usually distinguished by size as follows:

Boulders	Larger than 6 in
Cobbles	6 to 3 in
Coarse aggregate	3 in to No. 4 sieve
Fine aggregate	No. 4 sieve to No. 200 sieve
Mineral filler	Material passing No. 200 sieve

Used in most concrete construction, normal-weight aggregates are obtained by draining riverbeds or mining and crunching formational material. Concrete made with normal-weight fine and coarse aggregates generally weights about 144 lb/ft^3.

Boulders and cobbles are generally not used in their as-mined size but are crushed to make various sizes of coarse aggregate and manufactured sand and mineral filler. Gravels and naturally occurring sand are produced by the action of water and weathering on glacial and river deposits. These materials have round, smooth surfaces and particle-size distributions that require minimal processing. These materials can be supplied in either coarse or fine-aggregate sizes.

Fine aggregates have 100% of their material passing the ⅜-in sieve. Coarse aggregates have the bulk of the material retained on the No. 4 sieve.

Aggregates comprise the greatest volume percentage in portland-cement concrete, mortar, or asphaltic concrete. In a portland-cement concrete mix, the coarse and fine aggregates occupy about 60 to 75% of the total mix volume. For asphaltic concrete, the aggregates represent 75 to 85% of the mix volume. Consequentially, the aggregates are not inert filler materials. The individual aggregate properties have demonstrable effects on the service life and durability of the material system in which the aggregate is used, such as portland-cement concrete, asphaltic concrete, mortar, or aggregate base.

The acceptability of a coarse or fine aggregate for use in concrete or mortar is judged by many properties including gradation, amount of fine material passing the No. 200 sieve, hardness, soundness, particle shape, volume stability, potential alkali reactivity, resistance to freezing and thawing, and organic impurities. For aggregates used in general building construction, property limits are provided in ASTM C33, ‘‘Specification for Concrete Aggregates,’’ C637, ‘‘Specification for Aggregates for Radiation-Shielding Concrete,’’ and C330, ‘‘Specification for Lightweight Aggregates for Structural Concrete.’’ For other types of construction, such as highways and airports, standards written by various trade or governmental organizations are available.

4.11.1 Gradation of Aggregates

The distribution of aggregate sizes in a concrete mix is important because it directly influences the amount of cement required for a given strength, workability of the mix (and amount of effort to place the mix in the forms), in-place durability, and overall economy. ASTM C33 provides ranges of fine- and coarse-aggregate grading limits. The latter are listed from Size 1 (3½ to 1½ in) to Size 8 (⅜ to No. 8). The

National Stone Association specifies a gradation for manufactured sand that differs from that for fine aggregate in C33 principally for the No. 100 and 200 sieves. The NSA gradation is noticeably finer (greater percentages passing each sieve). The fine materials, composed of angular particles, are rock fines, as opposed to silts and clays in natural sand, and contribute to concrete workability.

The various gradations provide standard sizes for aggregate production and quality-control testing. They are conducive to production of concrete with acceptable properties. Caution should be exercised, however, when standard individual grading limits are used. If the number of aggregate sizes are limited or there is not sufficient overlap between aggregates sizes, an acceptable or economical concrete may not be attainable with acceptably graded aggregates. The reason for this is that the combined gradation is gap graded. The ideal situation is a dense or well-graded size distribution that optimizes the void content of the combined aggregates (Art. 4.17). It is possible, however, to produce acceptable concrete with individual aggregates that do not comply with the standard limits but that can be combined to produce a dense gradation.

4.11.2 Amount of Fine Material Passing the No. 200 Sieve

The material passing the No. 200 sieve is clay, silt, or a combination of the two. It increases the water demand of the aggregate. Large amounts of materials smaller than No. 200 may also indicate the presence of clay coatings on the coarse aggregate that would decrease bond of the aggregate to the cement matrix. A test method is given in ASTM C117, ‘‘Materials Finer than 75 μm Sieve in Mineral Aggregates by Washing.’’

4.11.3 Hardness

Coarse-aggregate hardness is measured by the Los Angeles Abrasion Test, ASTM C131 or C595. These tests break the aggregate down by impacting it with steel balls in a steel tumbler. The resulting breakdown is not directly related to the abrasion an aggregate receives in service, but the results can be empirically related to concretes exhibiting service lives.

4.11.4 Soundness

Aggregate soundness is measured by ASTM C88, ‘‘Test Method for Soundness of Aggregates by Use of Sodium Sulfate or Magneisum Sulfate.’’ This test measures the amount of aggregate degradation when exposed to alternating cycles of wetting and drying in a sulfate solution.

4.11.5 Particle Shape

Natural sand and gravel have a round, smooth particle shape. Crushed aggregate (coarse and fine) may have shapes that are flat and elongated, angular, cubical, disk, or rodlike. These shapes result from the crushing equipment employed and the aggregate mineralogy. Extreme angularity and elongation increase the amount of cement required to give strength, difficulty in finishing, and effort required to pump the concrete. Flat and elongated particles also increase the amount of required mixing water.

The bond between angular particles is greater than that between smooth particles. Properly graded angular particles can take advantage of this property and offset the increase in water required to produce concrete with cement content and strength equal to that of a smooth-stone mix.

4.11.6 Potential Alkali Reactivity

Aggregates that contain certain forms of silicas or carbonates may react with the alkalies present in portland cement (sodium oxide and potassium oxide). The reaction product cracks the concrete or may create pop-outs at the concrete surface. The reaction is more pronounced when the concrete is in a warm, damp environment.

Testing for potentially reactive aggregates is difficult, since the available tests do not yield consistent answers. Tests for aggregate potential alkali reactivity can be categorized as pre- or post-concrete and chemical or physical. Of the three preconcrete tests, one is chemical. The standard chemical test (ASTM C289) is a screening test that should only be used for an initial aggregate screening. Experience has shown the test will give false positive reactions of potentially reactive aggregates. The old mortar bar test (ASTM C227) is very slow and may be too lenient. The rapid immersion mortar bar test (ASTM C1260) is a harsher test but can produce results in two weeks. Potential alkali reactivity can be determined in concrete by observation or using a uranal acetate ultraviolet light test procedure. Petrographic analysis of aggregates and hardened concrete can be used to evaluate the potential for alkali silica reactivity (ASR). Long-term field experience with available aggregate sources is the best predictor of ASR.

4.11.7 Resistance to Freezing and Thawing

The pore structure, absorption, porosity, and permeability of aggregates are especially important if they are used to make concrete exposed to repeated cycles of freezing and thawing. Aggregates that become critically saturated and then freeze cannot accommodate the expansion of the frozen water. Empirical data show that freeze-thaw deterioration is caused by the coarse aggregates and not the fine. A method prescribed in ‘‘Test Method for Resistance of Concrete to Rapid Freezing and Thawing,’’ ASTM C666, measures concrete performance by weight changes, a reduction in the dynamic modulus of elasticity, and increases in sample length.

4.11.8 Impurities in Aggregates

Erratic setting times and rates of hardening may be caused by organic impurities in the aggregates, primarily the sand. The presence of these impurities can be investigated by a method given in ‘‘Test Method for Organic Impurities in Fine Aggregates for Concrete,’’ ASTM C40.

Pop-outs and reduced durability can be caused by soft particles, chert, clay lumps and other friable particles, coal, lignite, or other lightweight materials in the aggregates. Coal and lignite may also cause staining of exposed concrete surfaces.

4.11.9 Volume Stability

Volume stability refers to susceptibility of aggregate to expansion when heated or to cyclic expansions and contractions when saturated and dried. Aggregates that are susceptible to volume change due to moisture should be avoided.

4.12 HEAVYWEIGHT AND LIGHTWEIGHT AGGREGATES

Heavyweight aggregates include magnetite, with a specific gravity δ of 4.3; barite, $\delta = 4.2$; limonite, $\delta = 3.8$; ferrophosphorus, $\delta = 6.3$; and steel shot or punchings, $\delta = 7.6$. Such heavyweight aggregates may be used instead of gravel or crushed stone to produce a dense concrete; for example, for shielding of nuclear reactors as specified in ASTM C637.

Lightweight Aggregates. These can be divided into two categories: structural and nonstructural. The structural lightweight aggregates are defined by ASTM C330 and C331. They are either manufactured (expanded clay, shale, or slate, or blast-furnace slag) or natural (scoria and pumice). These aggregates produce concretes generally in the strength range of 3000 to 4000 psi; higher strengths are attainable and are discussed in Art. 4.17. The air-dry unit weight of normal strength lightweight concrete (less than 5000 psi) ranges from 100 to 115 pcf. High-performance lightweight concrete has unit weights in the range of 120 pcf.

The common nonstructural lightweight aggregates (ASTM C332) are vermiculite and perlite, although scoria and pumice can also be used. These materials are used in insulating concretes for soundproofing and nonstructural floor toppings.

Lightweight aggregates produce concrete with low thermal conductivities, which equate to good fire protection. When concrete is exposed to extreme heat, the moisture present within the concrete rapidly changes from a liquid to steam having a volume of up to 15 times larger. The large number and large sizes of pores within lightweight aggregates create pressure-relief regions.

ADMIXTURES FOR CONCRETE

Admixtures are anything other than portland cement, water, and aggregates that are added to a concrete mix to modify its properties. Included in this definition are chemical admixtures (ASTM C494 and C260), mineral admixtures such as fly ash (C618) and silica fume, corrosion inhibitors, colors, fibers, and miscellaneous (pumping aids, dampproofing, gas-forming, permeability-reducing agents).

4.13 CHEMICAL AND MINERAL ADMIXTURES

Chemical admixtures used in concrete generally serve as water reducers, accelerators, set retarders, or a combination. ASTM C494, ‘‘Standard Specification for Chemical Admixtures for Concrete,’’ contains the following classification:

Type	Property
A	Water reducer
B	Set retarder
C	Set accelerator
D	Water reducer and set retarder
E	Water reducer and set accelerator
F	High-range water reducer
G	High-range water reducer and set retarder

High-range admixtures reduce the amount of water needed to produce a concrete of a specific consistency by 12% or more.

4.13.1 Water-Reducing Admixtures

These decrease water requirements for a concrete mix by chemically reacting with early hydration products to form a monomolecular layer of admixture at the cement-water interface. This layer isolates individual particles of cement and reduces the energy required to cause the mix to flow. Thus, the mix is ''lubricated'' and exposes more cement particles for hydration.

The Type A admixture allows the amount of mixing water to be reduced while maintaining the same mix slump. Or at a constant water-cement ratio, this admixture allows the cement content to be decreased without loss of strength. If the amount of water is not reduced, slump of the mix will be increased and also strength will be increased because more of the cement surface area will be exposed for hydration. Similar effects occur for Type D and E admixtures. Typically, a reduction in mixing water of 5 to 10% can be expected.

Type F and G admixtures are used where there is a need for high-workability concrete. A concrete without an admixture typically has a slump of 2 to 3 in. After the admixture is added, the slump may be in the range of 8 to 10 in without segregation of mix components. These admixtures are especially useful for mixes with a low water-cement ratio. Their 12 to 30% reduction in water allows a corresponding reduction in cementitious material.

The water-reducing admixtures are commonly manufactured from lignosulfonic acids and their salts, hydroxylated carboxylic acids and their salts, or polymers of derivatives of melamines or naphthalenes or sulfonated hydrocarbons. The combination of admixtures used in a concrete mix should be carefully evaluated and tested to ensure that the desired properties are achieved. For example, depending on the dosage of admixture and chemistry of the cement, it is possible that a retarding admixture will accelerate the set. Note also that all normal-set admixtures will retard the set if the dosage is excessive. Furthermore, because of differences in percentage of solids between products from different companies, there is not always a direct correspondence in dosage between admixtures of the same class. Therefore, it is important to consider the chemical composition carefully when evaluating competing admixtures.

Superplasticizers are high-range water-reducing admixtures that meet the requirements of ASTM C494 Type F or G. They are often used to achieve high-strength concrete by use of a low water-cement ratio with good workability and low segregation. They also may be used to produce concrete of specified strengths with less cement at constant water-cement ratio. And they may be used to produce self-compacting, self-leveling flowing concretes, for such applications as long-distance pumping of concrete from mixer to formwork or placing concrete in forms congested with reinforcing steel. For these concretes, the cement content or water-cement ratio is not reduced, but the slump is increased substantially without causing segregation. For example, an initial slump of 3 to 4 in for an ordinary concrete mix may be increased to 7 to 8 in without addition of water and decrease in strength.

Superplasticizers may be classified as sulfonated melamine-formaldehyde condensates, sulfonated naphthaline-formaldehyde condensates, modified lignosulfonates, or synthetic polymers.

4.13.2 Air-Entraining Admixtures

These create numerous microscopic air spaces within concrete to protect it from degradation due to repeated freezing and thawing or exposure to aggressive chemicals. For concrete exposed to repeated cycles of freezing and thawing, the air gaps provide room for expansion of external and internal water, which otherwise would damage the concrete.

Since air-entrained concrete bleeds to a lesser extent than non-air-entrained, there are fewer capillaries extending from the concrete matrix to the surface. Therefore, there are fewer avenues available for ingress of aggressive chemicals into the concrete.

The ‘‘Standard Specification for Air-Entraining Admixtures for Concrete,’’ ASTM C260, covers materials for use of air-entraining admixtures to be added to concrete in the field. Air entrainment may also be achieved by use of Types IIA and IIIA portland cements (Art. 4.2.2).

4.13.3 Set-Accelerating Admixtures

These are used to decrease the time from the start of addition of water to cement to initial set and to increase the rate of strength gain of concrete. The most commonly used set-accelerating admixture is calcium chloride. Its use, however, is controversial in cases where reinforcing or prestressing steel is present. The reason is that there is a possibility that the accelerator will introduce free chloride ions into the concrete, thus contributing to corrosion of the steel. An alternative is use of one of many admixtures not containing chloride that are available.

4.13.4 Retarding Admixtures

To some extent, all normal water-reducing admixtures retard the initial set of concrete. A Type B or D admixture will allow transport of concrete for a longer time before initial set occurs. Final set also is delayed. Hence, precautions should be taken if retarded concrete is to be used in walls.

Depending on the dosage and type of base chemicals in the admixture, initial set can be retarded for several hours to several days. A beneficial side effect of retardation of initial and final sets is an increase in the compressive strength of the concrete. A commonly used Type D admixture provides higher 7- and 28-day strengths than a Type A when used in the same mix design.

4.13.5 Mineral Admixtures

Fly ashes, pozzolans, and microsilicates are included in the mineral admixture classification (Arts. 4.9 and 4.10). Natural cement (Art. 4.4) is sometimes used as an admixture.

4.13.6 Corrosion Inhibitors

Reinforcing steel in concrete usually is protected against corrosion by the high alkalinity of the concrete, which creates a passivating layer at the steel surface. This layer is composed of ferric oxide, a stable compound. Within and at the surface of the ferric oxide, however, are ferrous-oxide compounds, which are more reactive. When the ferrous-oxide compounds come into contact with aggressive substances, such as chloride ions, they react with oxygen to form solid, iron-oxide corrosion products. These produce a fourfold increase in volume and create an expansion force greater than the concrete tensile strength. The result is deterioration of the concrete.

For corrosion to occur, chloride in the range of 1.0 to 1.5 lb/yd^3 must be present. If there is a possibility that chlorides may be introduced from outside the concrete matrix, for example, by deicing salts, the concrete can be protected by lowering the water-cement ratio, or increasing the amount of cover over the reinforcing steel, or entraining air in the concrete, or adding a calcium-nitrate admixture, or adding an internal-barrier admixture, or cathodic protection, or a combination of these methods.

To inhibit corrosion, calcium-nitrate admixtures are added to the concrete at the time of batching. They do not create a physical barrier to chloride ion ingress. Rather, they modify the concrete chemistry near the steel surface. The nitrite ions oxidize ferrous oxide present, converting it to ferric oxide. The nitrite is also absorbed at the steel surface and fortifies the ferric-oxide passivating layer. For a calcium-nitrite admixture to be effective, the dosage should be adjusted in accordance with the exposure condition of the concrete to corrosive agents. The greater the exposure, the larger should be the dosage. The correct dosage can only be determined on a project-by-project basis with data for the specific admixture proposed.

Internal-barrier admixtures come in two groups. One comprises waterproofing and dampproofing compounds (Art. 4.15). The second consists of agents that create an organic film around the reinforcing steel, supplementing the passivating layer. This type of admixture is promoted for addition at a fixed rate regardless of expected chloride exposure.

4.13.7 Coloring Admixtures

Colors are added to concrete for architectural reasons. They may be mineral oxides or manufactured pigments. Raw carbon black, a commonly used material for black color, greatly reduces the amount of entrained air in a mix. Therefore, if black concrete is desired for concrete requiring air-entrainment (for freeze-thaw or aggressive chemical exposure), either the carbon black should be modified to entrain air or an additional air-entraining agent may be incorporated in the mix. The mix design should be tested under field conditions prior to its use in construction. Use of color requires careful control of materials, batching, and water addition in order to maintain a consistent color at the jobsite.

4.14 FIBERS FOR CONCRETE MIXES

As used in concrete, fibers are discontinuous, discrete units. They may be described by their aspect ratio, the ratio of length to equivalent diameter. Fibers find their greatest use in crack control of concrete flatwork, especially slabs on grade.

The most commonly used types of fibers in concrete are synthetics, which include polypropylene, nylon, polyester, and polyethylene materials. Specialty synthetics include aramid, carbon, and acrylic fibers. Glass-fiber-reinforced concrete is made using E-glass and alkali-resistant (AR) glass fibers. Steel fibers are chopped high-tensile or stainless steel.

Fibers should be dispersed uniformly throughout a mix. Orientation of the fibers in concrete generally is random. Conventional reinforcement, in contrast, typically is oriented in one or two directions, generally in planes parallel to the surface. Further, welded-wire fabric or reinforcing steel bars must be held in position as concrete is placed. Regardless of the type, fibers are effective in crack control because they provide omnidirectional reinforcement to the concrete matrix. With steel fibers, impact strength and toughness of concrete may be greatly improved and flexural and fatigue strengths enhanced.

Synthetic fibers are typically used to replace welded-wire fabric as secondary reinforcing for crack control in concrete flatwork. Depending on the fiber length, the fiber can limit the size and spread of plastic shrinkage cracks or both plastic and drying shrinkage cracks. Although synthetic fibers are not designed to provide structural properties, slabs tested in accordance with ASTM E72, ‘‘Standard Methods of Conducting Strength Tests of Panels for Building Construction,’’ showed that test slabs reinforced with synthetic fibers carried greater uniform loads than slabs containing welded wire fabric. While much of the research for synthetic fibers has used reinforcement ratios greater than 2%, the common field practice is to use 0.1% (1.5 lb/yd^3). This dosage provides more cross-sectional area than 10-gage welded-wire fabric. The empirical results indicate that cracking is significantly reduced and is controlled. A further benefit of fibers is that after the initial cracking, the fibers tend to hold the concrete together.

Aramid, carbon, and acrylic fibers have been studied for structural applications, such as wrapping concrete columns to provide additional strength. Other possible uses are for corrosion-resistance structures. The higher costs of the specialty synthetics limit their use in general construction.

Glass-fiber-reinforced concrete (GFRC) is used to construct many types of building elements, including architectural wall panels, roofing tiles, and water tanks. The full potential of GFRC has not been attained because the E-glass fibers are alkali reactive and the AR-glass fibers are subject to embrittlement, possibly from infiltration of calcium-hydroxide particles.

Steel fibers can be used as a structural material and replace conventional reinforcing steel. The volume of steel fiber in a mix ranges from 0.5 to 2%. Much work has been done to develop rapid repair methods using thin panels of densely packed steel fibers and a cement paste squeegeed into the steel matrix. American Concrete Institute Committee 544 states in ‘‘Guide for Specifying, Mixing, Placing, and Finishing Steel Fiber Reinforced Concrete,’’ ACI 544.3R, that, in structural members such as beams, columns, and floors not on grade, reinforcing steel should be provided to support the total tensile load. In other cases, fibers can be used to reduce section thickness or improve performance. See also ACI 344.1R and 344.2R.

4.15 MISCELLANEOUS ADMIXTURES

There are many miscellaneous concrete additives for use as pumping aids and as dampproofing, permeability-reducing, gas-forming agents.

Pumping aids are used to decrease the viscosity of harsh or marginally pumpable mixes. Organic and synthetic polymers, fly ash, bentonite, or hydrated lime may be used for this purpose. Results depend on concrete mix, including the effects of increased water demand and the potential for lower strength resulting from the increased water-cement ratio. If sand makes the mix marginally pumpable, fly ash is the preferred pumping additive. It generally will not increase the water demand and it will react with the calcium hydroxide in cement to provide some strength increase.

Dampproofing admixtures include soaps, stearates, and other petroleum products. They are intended to reduce passage of water and water vapor through concrete. Caution should be exercised when using these materials inasmuch as they may increase water demand for the mix, thus increasing the permeability of the concrete. If dense, low-permeable concrete is desired, the water-cement ratio should be kept to a maximum of 0.50 and the concrete should be well vibrated and damp cured.

Permeability of concrete can be decreased by the use of fly ash and silica fume as admixtures. Also, use of a high-range water-reducing admixture and a water-cement ratio less than 0.50 will greatly reduce permeability.

Gas-forming admixtures are used to form lightweight concrete. They are also used in masonry grout where it is desirable for the grout to expand and bond to the concrete masonry unit. They are typically an aluminum powder.

MORTARS AND CONCRETES

4.16 MORTARS

Mortars are composed of a cementitious material, fine aggregate, sand, and water. They are used for bedding unit masonry, for plasters and stuccoes, and with the addition of coarse aggregate, for concrete. Here consideration is given primarily to those mortars used for unit masonry and plasters.

Properties of mortars vary greatly, being dependent on the properties of the cementitious material used, ratio of cementitious material to sand, characteristics and grading of the sand, and ratio of water to solids.

4.16.1 Packaging and Proportioning of Mortar

Mortars are usually proportioned by volume. A common specification is that not more than 3 ft^3 of sand be used with 1 ft^3 of cementitious material. Difficulty is sometimes encountered, however, in determining just how much material constitutes a cubic foot: a bag of cement (94 lb) by agreement is called a cubic foot in proportioning mortars or concretes, but an actual cubic foot of lime putty may be used in proportioning mortars. Since hydrated limes are sold in 50-lb bags (Art. 4.5.3), each of which makes somewhat more than a cubic foot of putty, weights of 40, 42, and 45 lb of hydrated lime have been used as a cubic foot in laboratory studies; but on the job, a bag is frequently used as a cubic foot. Masonry cements are sold in bags containing 70 to 80 lb (Art. 4.8), and a bag is considered a cubic foot.

4.16.2 Properties of Mortars

Table 4.4 lists types of mortars as a guide in selection for unit masonry.

Workability is an important property of mortars, particularly of those used in conjunction with unit masonry of high absorption. Workability is controlled by the character of the cement and amount of sand. For example, a mortar made from 3 parts sand and 1 part slaked lime putty will be more workable than one made from 2 parts sand and 1 part portland cement. But the 3:1 mortar has lower strength. By proper selection or mixing of cementitious materials, a satisfactory compromise may usually be obtained, producing a mortar of adequate strength and workability.

Water retention—the ratio of the flow after 1-min standard suction to the flow before suction—is used as an index of the workability of mortars. A high value of water retention is considered desirable for most purposes. There is, however, a wide variation in water retention of mortars made with varying proportions of cement and lime and with varying limes. The "Standard Specification for Mortar for Unit Masonry," ASTM C270, requires mortar mixed to an initial flow of 100 to 115, as determined by the test method of ASTM C109, to have a flow after suction of at least 75%.

Strength of mortar is frequently used as a specification requirement, even though it has little relation to the strength of masonry. (See, for example, ASTM C270,

TABLE 4.4 Types of Mortar

	Parts by volume				
Mortar type	Portland cement	Masonry cement	Hydrated lime or lime putty	Aggregate measured in damp, loose condition	Min avg compressive strength of three 2-in cubes at 28 days, psi
M	1	1			2500
	1		¼		
S	½	1			1800
	1		Over ¼ to ½	Not less than 2¼ and not more than 3 times the sum of the volumes of the cements and limes used	
N		1			750
	1		Over ½ to 1¼		
O		1			350
	1		Over 1¼ to 2½		
K	1		Over 2½ to 4		75
PL	1		¼ to ½		2500
PM	1	1			2500

C780, and C476). The strength of mortar is affected primarily by the amount of cement in the matrix. Other factors of importance are the ratio of sand to cementing material, curing conditions, and age when tested.

Volume change of mortars constitutes another important property. Normal volume change (as distinguished from unsoundness) may be considered as the shrinkage during early hardening, shrinkage on drying, expansion on wetting, and changes due to temperature.

After drying, mortars expand again when wetted. Alternate wetting and drying produces alternate expansion and contraction, which apparently continues indefinitely with portland-cement mortars.

Coefficients of thermal expansion of several mortars, reported in ''Volume Changes in Brick Masonry Materials,'' *Journal of Research of the National Bureau of Standards,* Vol. 6, p. 1003, ranged from 0.38×10^{-5} to 0.60×10^{-5} for masonry-cement mortars; from 0.41×10^{-5} to 0.53×10^{-5} for lime mortars, and from 0.42×10^{-5} to 0.61×10^{-5} for cement mortars. Composition of the cementitious material apparently has little effect on the coefficient of thermal expansion of a mortar.

4.16.3 High-Bond Mortars

When polymeric materials, such as styrene-butadiene and polyvinylidene chloride, are added to mortar, greatly increased bonding, compressive, and shear strengths result. To obtain high strength, the other materials, including sand, water, Type I or III portland cement, and a workability additive, such as pulverized ground limestone or marble dust, must be of quality equal to that of the ingredients of standard mortar. The high strength of the mortar enables masonry to withstand appreciable bending and tensile stresses. This makes possible thinner walls and prelaying of single-wythe panels that can be hoisted into place.

4.17 PORTLAND-CEMENT CONCRETE

Portland-cement concrete is a mixture of portland cement, water, coarse and fine aggregates, and admixtures proportioned to form a plastic mass capable of being cast, placed, or molded into forms that will harden to a solid mass. The desirable properties of plastic concrete are that it be workable, placeable and nonsegregating, and that it set in the desired time. The hardened concrete should provide the desired service properties:

1. Strength (compressive and flexural)
2. Durability (lack of cracks, resistance to freezing and thawing and to chemical attacks, abrasion resistance, and air content)
3. Appearance (color, lack of surface imperfections)

Each of these properties affects the final cost of the mix design and the cost of the in-place concrete. These properties are available from normal-weight, lightweight, and heavyweight concretes.

4.17.1 Normal-Weight Concrete

The nominal weight of normal concrete is 144 lb/ft^3 for non-air-entrained concrete, but is less the air-entrained concrete. (The weight of concrete plus steel reinforcement is often assumed as 150 lb/ft^3.)

Strength for normal-weight concrete ranges from 2000 to 20,000 psi. It is generally measured using a standard test cylinder 6 in in diameter by 12 in high. The strength of a concrete is defined as the average strength of two cylinders taken from the same load and tested at the same age. Flexural beams $6 \times 6 \times 20$ in may be used for concrete paving mixes. The strength gains of air-entrained and non-air-entrained concretes are graphically shown in Fig. 9.2.

As illustrated in Fig. 9.2, the strength of a given mix is determined by the water-cement ratio (W/C), and whether or not air entraining is used. Other factors are the maximum-size aggregate and the desired fluidity (slump) of the concrete at the point of placement. When no historical record is available for the aggregates and cements to be used, the water-cement ratios in Table 9.2 can provide guidance for the initial designs.

Each combination of coarse and fine aggregates has a specific water demand for a given mix fluidity, or slump. Two general guidelines are:

1. For a constant slump, the water demand increases with increase in maximum-size aggregate.
2. For a constant maximum-size aggregate, as the slump increases, the water demand increases.

There are many different methods for designing a normal-weight concrete mix. A standard method is given in ACI 211, ‘‘Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete.’’ See also Art. 9.10.

Workability of a concrete is the property most important to contractors who must place the concrete into forms and finish it. Workability includes the properties of cohesiveness, plasticity, and nonsegregation. It is greatly influenced by aggregate shape and gradation. Mixes that are hard to pump, place, and finish include those deficient in fines, those with flat and elongated aggregates, and those with an excessive amount of fines (sand and cement). If the sand is deficient in fines, workability can be increased by addition of 30 to 50 lb/yd^3 of fly ash. The most effective method of producing workable concrete is to employ a well graded, combined aggregate gradation.

Modulus of elasticity of normal-weight concrete is between 2,000,000 and 6,000,000 psi. An estimate of the modulus of elasticity for normal-weight concrete with compressive strengths f'_c between 3000 and 5000 psi can be obtained by multiplying the square root of f'_c by 57,000. Above 5000 psi, the modulus should be determined using the procedure of ASTM C469. [See also Eq. (4.1) in Art. 4.17.2.]

Volume changes occur as either drying shrinkage, creep, or expansion due to external thermal sources. Drying shrinkage causes the most problems, because it produces cracks in the concrete surface. The primary cause of drying shrinkage cracks is an excessive amount of water in the mix. The water has two effects. First, it increases the water-cement ratio (W/C), weakening the concrete. Second, additional water beyond that needed for hydration of the cement creates an excessive number of bleed channels to exposed surfaces. When the cement paste undergoes its normal drying shrinkage, these channels cannot provide any resistance to penetration of water or aggressive chemicals.

Creep is a time-dependent deformation of concrete that occurs after an external load is applied to the concrete. It is an important consideration in design of prestressed concrete.

Concrete expands when heated and contracts when cooled. Coefficients of thermal expansion range from 3.2 to 7.0 millionths per °F. The most notable result of the response of concrete to thermal changes is the movement of external walls, which may bow because of temperature differentials.

Normal-weight concrete that is not designed for fire exposure expands on being heated. A side effect is some strength loss and a reduction in the modulus of elasticity.

Resistance to freezing and thawing can be accomplished by proper air entrainment in the concrete, use of a mix with a minimum water content, and proper curing of the concrete. Table 9.3 provides guidelines for the amount of air to use based upon exposure and maximum aggregate size.

Chemical attack may be internal (alkali-aggregate reaction) or external (sulfate attack or an aggressive service environment). In either case, the basic concerns are the characteristics of the available materials and the environment in which the concrete will be used. Alkali-reactive aggregates should be avoided, but if they must be used, a low-alkali cement complying with ASTM C150 Type II Modified should be selected. If sulfate attack is a concern, a low W/C (0.45 maximum) and air entrainment should be used with either a C150 Type V cement or a C150 Type II cement with C618 Type F fly ash. For protection from attack by other chemicals, a low W/C (0.45 maximum), more concrete cover over the reinforcing steel, a corrosion-protection additive, or a latex-modified concrete should be used. The American Concrete Institute ‘‘Building Code Requirements for Reinforced Concrete,’’ ACI 318, contains requirements for special exposure conditions.

Abrasion resistance is a concern with pavements and hydraulic structures. Both require use of sound, durable, hard-rock aggregates, low W/C, and well-cured concrete.

Acceptable appearance depends on good workmanship and a supply of consistent materials. The formwork should be watertight and properly oiled before concrete placement. Forms should not be made of wood that will release sugars into the concrete and create a retarded surface finish. During concrete placement, the concrete should have consistent workability. The forms should be uniformly and consistently vibrated to consolidate the concrete.

(‘‘Standard Practice for Selecting Proportions for Normal Heavyweight, and Mass Concrete,’’ ACI 211.1, and ‘‘Guide for Use of Normal Weight Aggregates in Concrete,’’ ACI 221.)

4.17.2 Lightweight Concrete

Concrete weighing considerably less than the 144 lb/ft^3 of normal-weight concrete may be produced by use of lightweight aggregates or by expanding or foaming the concrete. Lightweight concrete is used principally to reduce the dead load of a structure and lower the cost of foundations. The light weight of the aggregates used for this type of concrete derives from the cellular structure of the particles. Hence, lightweight-aggregate concrete as well as foamed and expanded concretes have excellent fire-protection capabilities because of the internal voids in the aggregates or the concrete itself. When lightweight aggregates are used, they may be both fine and coarse, or lightweight coarse and normal-weight fine (sand), or normal-weight coarse and lightweight fine. The last combination is the least often used. Unit weights range from 90 lb/ft^3 (all aggregates lightweight) to 115 lb/ft^3 (sand lightweight). Typically, compressive strengths range from 2500 to 4000 psi. High-strength lightweight concretes, however, have been produced with maximum unit weights of 125 lb/ft^3 and strengths from 6000 to 9000 psi. Structural lightweight concretes are defined by the ACI as concretes with a 28-day compressive strength more than 2500 psi and air-dry unit weight of 115 lb/ft^3 or less.

The variable amount of water absorbed in the voids of lightweight aggregates makes use of W/C difficult in design of a lightweight-aggregate mix (Table 4.5). Air entrainment of 4 to 6% is desirable to prevent segregation. Maximum size of the coarse aggregate should not exceed half the depth of cover over the reinforcing steel.

Lightweight-aggregate concrete exposed to sulfates should have a compressive strength ranging from 3750 to 4750 psi (see ACI 318). For marine structures, the W/C should not exceed 0.40 and at least seven bags of cement should be used per cubic yard of concrete.

The modulus of elasticity E_c of lightweight concrete generally ranges from 1,500,000 to 3,000,000 psi. It may be estimated from

$$E_c = w^{1.5}\sqrt{f'_c} \tag{4.1}$$

where w = unit weight of concrete, lb/ft^3
f'_c = 28-day compressive strength of concrete, psi

Volume changes occur in lightweight concrete as in normal-weight concrete, but lightweight concrete is stabler when exposed to heat. Drying shrinkage causes the most undesirable volume changes, because it produces cracks in the surfaces of the concrete. The primary cause of drying-shrinkage cracks is excessive water in the mix. The water has two effects. First, it increases the W/C and weakens the concrete. Second, the additional water beyond that needed for hydration of the cement creates an excessive number of bleed channels to the exposed surfaces. When the cement paste undergoes normal drying shrinkage, these channels cannot provide any resistance to ingress of aggressive chemicals.

Creep is an important concern for lightweight concrete, as it is for normal-weight concrete, especially for prestressed concrete.

(“Standard Practice for Selecting Proportions for Structural Lightweight Concrete,” ACI 211.2, and “Guide for Structural Lightweight Aggregate Concrete,” ACI 213.)

TABLE 4.5 Approximate Relationship between Cement Content and Compressive Strength

Compressive strength f'_c, psi	Aggregates all lightweight, lb/yd^3	Sand aggregate lightweight, lb/yd^3
2500	400–510	400–510
3000	440–560	420–560
4000	530–660	490–660

4.17.3 Heavyweight Concrete

Concretes made with heavyweight aggregates are used for shielding and structural purposes in construction of nuclear reactors and other structures exposed to high-intensity radiation (see Art. 4.12). Heavyweight aggregates are used where heavyweight is needed, such as ship's ballast and encasement of underwater pipes, and for making shielding concretes because absorption of such radiation is proportional to density, and consequently, these aggregates have greater capacity for absorption than those ordinarily used for normal concrete. With such aggregates, concrete weighing up to about 385 lb/ft^3 can be produced.

Concrete made with limonite or magnetite can develop densities of 210 to 224 lb/ft^3 and compressive strengths of 3200 to 5700 psi. With barite, concrete may weigh 230 lb/ft^3 and have a strength of 6000 psi. With steel punchings and sheared bars as coarse aggregate and steel shot as fine aggregate, densities of 250 to 288 lb/ft^3 and strengths of about 5600 psi can be attained. Generally, grading of aggregates and mix proportions are similar to those used for normal concrete.

The properties of heavyweight concrete are similar to those of normal-weight concrete. Mixing and placing operations, however, are more difficult than those for normal-weight concrete, because of segregation. Good grading, high cement content, low W/C, and air entrainment should be employed to prevent segregation. Sometimes, heavyweight aggregates are grouted in place to avoid segregation. Heavyweight concretes usually do not have good resistance to weathering or abrasion.

(''Recommended Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete,'' ACI 211.1.)

4.17.4 High-Performance Concretes

These concretes either have a high design strength (more than 6000 psi for normal-weight concrete and 5000 psi for lightweight concrete) or will be subjected to severe service environments. The differences between high-performance concretes and normal-weight concretes is that the former have lower W/C and smaller maximum aggregate size. ACI 318 specifies the W/C and compressive strengths for concrete in severe exposures and the maximum chloride-ion content of concrete. High-performance concrete is defined by either durability or strength-performance characteristics. Durability characteristics are resistance to freeze-thaw, scaling, abrasion, and chloride permeability. The strength characteristics have been defined in four grades as shown in Table 4.6. (See also Art. 4.17.1)

High-strength, portland-cement concretes generally incorporate in the mix fly ash, silica fume, or superplasticizers, or a combination of these admixtures. A retarder is often beneficial in controlling early hydration. The W/C may be as small as 0.25. The maximum size of aggregate should generally be limited to ½ in.

With superplasticizers, relatively high strengths can be achieved at early ages, such as 7-day strengths of normal concrete in 3 days and 28-day strengths in 7 days. Compressive strengths exceeding 10,000 psi can be achieved in 90 days.

Aside from reduction in W/C, the use of superplasticizers in production of high-strength concretes does not require significant changes in mix proportioning. An increase in the range of sand content of about 5%, however, may help avoid a harsh mix. Curing is very important, because strength gain halts when water is no longer available for hydration. Also, it is important that proper quantities of air-entraining admixtures be determined by trial. Some air loss may result when melamine- or

TABLE 4.6 High-Performance Concrete Strength Characteristics

Characteristic	Grade 1	Grade 2	Grade 3	Grade 4
Compressive strength, ksi	$6 \leq X < 8$	$8 \leq X < 10$	$10 \leq X < 14$	$X \geq 14$
Modulus of elasticity, 10^3 ksi	$4 \leq X < 6$	$6 \leq X < 7.5$	$X \geq 7.5$	
Shrinkage, microstrain, in/in	$600 \leq X < 800$	$400 \leq X < 600$	$X < 400$	
Creep, microstrain, in/in	$0.41 < X \leq 0.52$	$0.31 < X \leq 0.41$	$0.21 < X \leq 0.31$	$X \leq 0.21$

naphthalene-based superplasticizers are used, whereas lignosulfonate-based water reducers may actually increase air content. Larger amounts of air-entraining agent may be needed for high-strength concretes, especially for low-slump mixes with high cement content and mixes with large amounts of some types of fly ash. Furthermore, some types of superplasticizers and air-entraining admixtures may not be compatible with each other.

(''State-of-the-Art Report on High-Strength Concrete,'' ACI 363.)

4.17.5 Nonstructural or Foamed Cellular Concretes

These are formed by the use of admixtures that generate or liberate gas bubbles in concrete in the plastic stage. Aluminum powder, which reacts with the alkalies in cement to release hydrogen, is generally used for this purpose, although hydrogen peroxide, which generates oxygen, or activated carbon, which liberates absorbed air, can be used. These foaming agents create stable, uniformly dispersed air spaces within the concrete when it sets. Perlite and vermiculite are most frequently used as aggregates. The resulting concrete may weigh 50 lb/ft^3 or less and have a compressive strength up to 2500 psi. Applications of such lightweight concretes include topping and soundproofing barriers over structural concrete slabs.

The effectiveness of the admixture is controlled by the duration of mixing, handling, and placing of the mix relative to the gas-generation rate. The amount of unpolished aluminum powder to be added to a mix may range from 0.005 to 0.02% by weight of cement under normal conditions. Larger quantities, however, may be used to produce lower-strength concretes. More aluminum may be needed at low temperatures to achieve the same amount of concrete expansion, for example, twice as much as 40°F as at 70°F. Furthermore, at low temperatures, to speed up gas generation, it may be necessary to add to the mix alkalies such as sodium hydroxide, hydrated lime, or trisodium phosphate. Also, to prevent the powder from floating on the surface of mixing water, the aluminum may be premixed with sand or combined with other admixtures.

Curing is very important. If good curing practices and jointing are not followed, extensive drying shrinkage may result.

4.18 POLYMER CONCRETES

Plastics with long-chain molecules, called polymers, are used in several ways to enhance concrete properties: replacement of portland cement, incorporation in a mix as an admixture, and impregnating hardened concrete.

Polymer concretes, such as methyl methacrylate and unsaturated polyester, in which a polymer replaces portland cement may have more than double the strength and modulus of elasticity of portland-cement concrete. Creep is less and resistance to freezing and thawing cycles is higher with the polymer concretes. After curing for a very short time, for example, overnight at room temperature, polymer concretes are ready for use, whereas ordinary concrete may have to cure for about a week before exposure to service loads.

Monomers and polymers may be used as admixtures for restoring and resurfacing deteriorated concrete surfaces. Latexes of methyl methacrylate, polyester, styrene, epoxy-styrene, furans, styrene-butadiene, and vinylidene chloride have been employed for these purposes. The resulting concrete hardens more rapidly than normal concrete. A polymer admixture may also be used to improve the bonding properties of portland cement. Inserted in a mix as an emulsion for this purpose, the admixture supplies a significant amount of water to the mix, which becomes available for hydration of the cement. The release of the water also sets the emulsion. Hence, moist curing is not desirable, inasmuch as the emulsion needs to dry to develop the desired strength. A grout or mortar containing the bonding admixture develops a higher bond strength when applied as a thin layer than as a thick one and the bond may be stronger than materials being joined.

Impregnation of concrete with polymers is sometimes used to harden surfaces exposed to heavy traffic. Strength and other properties of the impregnated concrete are similar to those of concrete in which polymers replace portland cement. Impregnation is achieved by first drying the concrete surface with heat and then soaking the surface with a monomer, such as methyl methacrylate, styrene, acrylonitrile, or tert-butyl styrene. It is subsequently cured with heat.

Slab Toppings. At least partly because of excellent adhesion, epoxies are formulated with sand and other fillers to provide surfacing materials for concrete. Unlike standard concrete topping, epoxy-based surfacing materials can be thin. They are especially useful for smoothing uneven, irregular surfaces. The epoxy cures quickly, allowing use of the surface in a short time.

Grout. Cracked concrete can be repaired with an epoxy grout. The grout is forced into cracks under pressure for deep penetration. Because of its good bonding strength, the epoxy grout can largely restore strength, while, at the same time, sealing the crack against penetration by liquids.

(‘‘Polymers in Concrete,’’ ACI 548; ‘‘Guide for the Use of Polymers in Concrete,’’ ACI 548.1; and ‘‘Polymer Modified Concrete,’’ SP-99, American Concrete Institute.)

4.19 CONCRETE MASONRY UNITS

A wide variety of manufactured products are produced from concrete and used in building construction. These include such items as concrete brick, concrete block or tile, concrete floor and roof slabs, precast wall panels, precast beams, and cast stone. These items are made both from normal dense concrete mixes and from mixes with lightweight aggregates. Concrete blocks are made with holes through them to reduce their weight and to enable masons to grip them.

Nominal size (actual dimensions plus width of mortar joint) of hollow concrete block usually is 8 × 8 × 16 in. Solid blocks often are available with nominal size of 4 × 8 × 16 in or 4 × 2½ × 8 in. For a list of modular sizes, see ‘‘Standard Sizes of Clay and Concrete Modular Units,’’ ANSI A62.3.

Properties of the units vary tremendously—from strong, dense, load-bearing units used under exposed conditions to light, relatively weak, insulating units used for roof and fire-resistant construction.

Many types of concrete units have not been covered by adequate standard specifications. For these units, reliance must be placed upon the manufacturer's specifications. Requirements for strength and absorption of concrete brick and block established by ASTM for Type I, Grades N-I and S-I (moisture-controlled), and Type II, Grades N-II and S-II (non-moisture-controlled), units are summarized in Table 4.7.

Manufactured concrete units have the advantage (or sometimes disadvantage) that curing is under the control of the manufacturer. Many methods of curing are used, from simply stacking the units in a more or less exposed location to curing under high-pressure steam. The latter method appears to have considerable merit in reducing ultimate shrinkage of the block. Shrinkage may be as small as ¼ to ⅜ in per 100 ft for concrete units cured with high-pressure steam. These values are about one-half as great as those obtained with normal atmospheric curing. Tests for moisture movement in blocks cured with high-pressure and high-temperature steam indicate expansions of from ¼ to ½ in per 100 ft after saturation of previously dried specimens.

BURNED-CLAY UNITS

Use of burned-clay structural units dates from prehistoric times. Hence durability of well-burned units has been adequately established through centuries of exposure in all types of climate.

Modern burned-clay units are made in a wide variety of sizes, shapes, colors, and textures to suit the requirements of modern architecture. They include such widely diverse units as common and face brick; hollow clay tile in numerous shapes, sizes, and designs for special purposes; ceramic tile for decorative and sanitary finishes, and architectural terra cotta for ornamentation.

Properties of burned-clay units vary with the type of clay or shale used as raw material, method of fabrication of the units, and temperature of burning. As a consequence, some units, such as salmon brick, are underburned, highly porous, and of poor strength. But others are almost glass hard, have been pressed and burned to almost eliminate porosity, and are very strong. Between these extremes lie most of the units used for construction.

4.20 BRICK—CLAY OR SHALE

Brick have been made in a wide range of sizes and shapes, from the old Greek brick, which was practically a 23-in cube of 12,650 in^3 volume, to the small Belgian brick, about 1¾ × 3⅜ × 4½ in with a total volume of only 27 in^3. The present common nominal sizes in the United States are 4 or 6 in thick by 2⅔ or 4 in high by 8 or 12 in long. For a list of modular sizes, see ‘‘Standard Sizes of Clay and Concrete Modular Masonry Units,’’ ANSI A62.3. Actual dimensions are smaller,

TABLE 4.7 Summary of ASTM Specification Requirements for Concrete Masonry Units

	Compressive strength, min, psi		Moisture content for Type I units, max, % of total absorption (average of 5 units) — Avg annual relative humidity, %			Moisture absorption, max, lb./ft^3 (average of 5 units) — Oven-dry weight of concrete, lb/ft^3		
	Avg of 5 units	Individual min	Over 75	75 to 50	Under 50	125 or more	105 to 125	Under 105
Concrete building brick, ASTM C55:								
N-I, N-II (high strength severe exposures)	3500	3000				10	13	15
S-I, S-II (general use, moderate exposures)	2500	2000				13	15	18
Linear shrinkage, %:								
0.03 or less			45	40	35			
0.03 to 0.45			40	35	30			
Over 0.045			35	30	25			
Solid, load-bearing units, ASTM C145:								
N-I, N-II (unprotected exterior walls below grade or above grade exposed to frost)	1800	1500				13	15	18
S-I, S-II (protected exterior walls below grade or above grade exposed to frost) Linear shrinkage, %; (Same as for brick)	1200	1000						20*
Hollow, load bearing units, ASTM C90:								
N-I, N-II (general use)	1000	800				13	15	18
S-I, S-II (above grade, weather protected) Linear shrinkage, %; (Same as for brick)	700	600						20*
Hollow, non-load-bearing units, ASTM C129 Linear shrinkage, %; (Same as for brick)	600	500						

*For units weighing less than 85 lb/ft^3.

TABLE 4.8 Physical Requirements for Clay or Shale Solid Brick

Grade	Compressive strength, flat, min, psi		Water absorption, 5-hr boil, max—%		Saturation* coefficient, max—%	
	Avg of 5	Individual	Avg of 5	Individual	Avg of 5	Individual
SW—Severe weathering	3000	2500	17.0	20.0	0.78	0.80
MW—Moderate weathering	2500	2200	22.0	25.0	0.88	0.90
NW—No exposure	1500	1250	No limit	No limit	No limit	No limit

*Ratio of 24-hr cold absorption to 5-hr boil absorption.

usually by the amount of the width of the mortar joint. Current specification requirements for strength and absorption of building brick are given in Table 4.8 (see ASTM C652, C62, and C216). Strength and absorption of brick from different producers vary widely.

Thermal expansion of brick may range from 0.0000017 per °F for fire-clay brick to 0.0000069 per °F for surface-clay brick. Wetting tests of brick indicated expansions varying from 0.0005 to 0.025%.

The thermal conductivity of dry brick as measured by several investigators ranges from 1.29 to 3.79 Btu/(hr)(ft^3)(°F)(in). The values are increased by wetting.

4.21 STRUCTURAL CLAY TILE

Structural clay tiles are hollow burned-clay masonry units with parallel cells. Such units have multitude of uses: as a facing tile for interior and exterior unplastered walls, partitions, or columns; as load-bearing tile in masonry constructions designed to carry superimposed loads; as partition tile for interior partitions carrying no superimposed load; as fireproofing tile for protection of structural members against fire; as furring tile for lining the inside of exterior walls; as floor tile in floor and roof construction; and as header tiles, which are designed to provide recesses for header units in brick or stone-faced walls. Units are available with the following ranges in nominal dimensions: 8 to 16 in in length, 4 in for facing tile to 12 in for load-bearing tile in height, and 2 in for facing tile to 12 in for load-bearing tile in thickness.

Two general types of tile are available—side-construction tile, designed to receive its principal stress at right angles to the axis of the cells, and end-construction tile designed to receive its principal stress parallel to the axis of the cells.

Tiles are also available in a number of surface finishes, such as opaque glazed tile, clear ceramic-glazed tile, nonlustrous glazed tile, and scored, combed, or roughened finishes designed to receive mortar, plaster, or stucco.

Requirements of the appropriate ASTM specifications for absorption and strength of several types of tile are given in Table 4.9 (see ASTM C34, C56, C57, C212, and C126 for details pertaining to size, color, texture, defects, etc.). Strength and absorption of tile made from similar clays but from different sources and manufacturers vary widely. The modulus of elasticity of tile may range from 1,620,000 to 6,059,000 psi.

TABLE 4.9 Physical Requirement Specification for Structural Clay Tile

Type and grade	Absorption, % (1 hr boiling)		Compressive strength, psi (based on gross area)			
			End-construction tile		Side-construction tile	
	Avg of 5 tests	Individual max	Min avg of 5 tests	Individual min	Min avg of 5 tests	Individual min
Loading-bearing (ASTM C34):						
LBX	16	19	1400	1000	700	500
LB	25	28	1000	700	700	500
Non-load-bearing (ASTM C56):						
NB		28				
Floor tile (ASTM C57):						
FT1		25	3200	2250	1600	1100
FT2		25	2000	1400	1200	850
Facing tile (ASTM C212):						
FTX	9 (max)	11				
FTS	16 (max)	19				
Standard			1400	1000	700	500
Special duty			2500	2000	1200	1000
Glazed units (ASTM C126)			3000	2500	2000	1500

LBX. Tile suitable for general use in masonry construction and adapted for use in masonry exposed to weathering. They may also be considered suitable for direct application of stucco.

LB. Tile suitable for general use in masonry where not exposed to frost action, or in exposed masonry where protected with a facing of 3 in or more of stone, brick, terra cotta, or other masonry.

NB. Non-load-bearing tile made from surface clay, shale, or fired clay.

FT 1 and FT 2. Tile suitable for use in flat or segmental panels or in combination tile and concrete ribbed-slab construction.

FTX. Smooth-face tile suitable for general use in exposed exterior and interior masonry walls and partitions, and adapted for use where tiles low in absorption, easily cleaned, and resistant to staining are required and where a high degree of mechanical perfection, narrow color range, and minimum variation in face dimensions are required.

FTS. Smooth or rough-texture face tile suitable for general use in exposed exterior and interior masonry walls and partitions and adapted for use where tile of moderate absorption, moderate variation in face dimensions, and medium color range may be used, and where minor defects in surface finish, including small handling chips, are not objectionable.

Standard. Tile suitable for general use in exterior or interior masonry walls and partitions.

Special duty. Tile suitable for general use in exterior or interior masonry walls and partitions and designed to have superior resistance to impact and moisture transmission, and to support greater lateral and compressive loads than standard tile construction.

Glazed units. Ceramic-glazed structural clay tile with a glossy or stain-mat finish of either an opaque or clear gaze, produced by the application of a coating prior to firing and subsequently made vitreous by firing.

4.22 CERAMIC TILES

Ceramic tile is a burned-clay product used primarily for decorative and sanitary effects. It is composed of a clay body on which is superimposed a decorative glaze.

The tiles are usually flat but vary in size from about ½ in square to more than 6 in. Their shape is also widely variable—squares, rectangles, and hexagons are the predominating forms, to which must be added coved moldings and other decorative forms. These tiles are not dependent on the color of the clay for their final color, since they are usually glazed. Hence, they are available in a complete color gradation from pure whites through pastels of varying hue to deep solid colors and jet blacks.

Properties of the base vary somewhat. In particular, absorption ranges from almost zero to about 15%. The glaze is required to be impervious to liquids and should not stain, crack, or craze.

Ceramic tiles are applied on a solid backing by means of a mortar or adhesive. They are usually applied with the thinnest possible mortar joint; consequently accuracy of dimensions is of greatest importance. Since color, size, and shape of tile are important, selection of tile should be based on the current literature of the manufacturer.

4.23 ARCHITECTURAL TERRA COTTA

The term ‘‘terra cotta’’ has been applied for centuries to decorative molded-clay objects whose properties are similar to brick. The molded shapes are fired in a manner similar to brick.

Terra cotta is frequently glazed to produce a desired color or finish. This introduces the problem of cracking or crazing of the glaze, particularly over large areas.

Structural properties of terra cotta are similar to those of clay or shale brick.

BUILDING STONES

Principal building stones generally used in the United States are limestones, marbles, granites, and sandstones. Other stones such as serpentine and quartzite are used locally but to a much lesser extent. Stone, in general, makes an excellent building material, if properly selected on the basis of experience; but the cost may be relatively high.

Properties of stone depend on what nature has provided. Therefore, the designer does not have the choice of properties and color available in some of the manufactured building units. The most the stone producer can do for purchasers is to avoid quarrying certain stone beds that have been proved by experience to have poor strength or poor durability.

4.24 PROPERTIES OF BUILDING STONES

Data on the strength of building stones are presented in Table 4.10, summarized from *U.S. National Bureau of Standards Technical Papers,* No. 123, B. S. Vol. 12;

TABLE 4.10 Strength Characteristics of Commercial Building Stones

Stone	Compressive strength, psi, range	Modulus of rupture, psi, range	Shear strength, psi, range	Tensile strength, psi, range	Elastic modulus, psi, range	Toughness		Wear resistance	
						Range	Avg	Range	Avg
Granite	7,700–60,000	1,430–5,190	2,000–4,800	600–1,000	5,700,000–8,200,000	8–27	13	43.9–87.9	60.8
Marble	8,000–50,000	600–4,900	1,300–6,500	150–2,300	7,200,000–14,500,000	2–23	6	6.7–41.7	18.9
Limestone	2,600–28,000	500–2,000	800–4,580	280–890	1,500,000–12,400,000	5–20	7	1.3–24.1	8.4
Sandstone	5,000–20,000	700–2,300	300–3,000	280–500	1,900,000–7,700,000	2–35	10	1.6–29.0	13.3
Quartzite	16,000–45,000					5–30	15		
Serpentine	11,000–28,000	1,300–11,000		800–1,600	4,800,000–9,600,000			13.3–111.4	46.9
Basalt	28,000–67,000					6–38	23		
Diorite	16,000–35,000					6–38	23		
Syenite	14,000–28,000								
Slate		6,000–15,000	2,000–3,600	3,000–4,300	9,800,000–18,000,000	10–56		5.6–11.7	7.7
Diabase						6–50	19		
Building limestone						3–8	4.4		

No. 305, Vol. 20, p. 191; No. 349, Vol. 21, p. 497; *Journal of Research of the National Bureau of Standards,* Vol. 11, p. 635; Vol. 25, p. 161). The data in Table 4.9 pertain to dried specimens. Strengths of saturated specimens may be either greater or less than that of completely dry specimens.

The modulus of rupture of dry slate is given in Table 4.10 as ranging from 6000 to 15,000 psi. Similar slates, tested wet, gave moduli ranging from 4700 to 12,300 psi. The ratio of wet modulus to dry modulus varied from 0.42 to 1.12 and averaged 0.73.

Data on the true specific gravity, bulk specific gravity, unit weights, porosity, and absorption of various stones are given in Table 4.11.

Permeability of stones varies with types of stone, thickness, and driving pressure that forces water through the stone. Table 4.12 represents data for the more common stones at three different pressures, as reported in ''Permeability of Stone,'' *U.S. National Bureau of Standards Technical Papers,* No. 305, Vol. 20, p. 191. The units of measurement of permeability are cubic inches of water that will flow through a square foot of a specimen ½ in thick in 1 hr.

Data on thermal expansion of building stones as given in Table 4.13 show that limestones have a wide range of expansion as compared with granites and slates.

Marble loses strength after repeated heating and cooling. A marble that had an original strength of 9174 psi had a strength after 50 heatings to 150°C of 8998 psi—a loss of 1.9%. After 100 heatings to 150°C, the strength was only 8507 psi, or a loss of 7.3%. The latter loss in strength was identical with that obtained on

TABLE 4.11 Specific Gravity and Porosity of Commercial Building Stones

Stone	Specific Gravity		Unit weight, lb per cu ft	Porosity, %	Absorption, %	
	True	Bulk			By weight	By volume
Granite	2.599–3.080	2.60–3.04	157–187	0.4–3.8	0.02–0.58	0.4–1.8
Marble	2.718–2.879	2.64–2.86	165–179	0.4–2.1	0.01–0.45	0.04–1.2
Limestone	2.700–2.860	1.87–2.69	117–175	1.1–31.0		6–15
Slate	2.771–2.898	2.74–2.89	168–180	0.1–1.7	0.00–1.63	0.3–2.0
Basalt		2.9–3.2				
Soapstone		2.8–3.0				
Gneiss		2.7–3.0				
Serpentine		2.5–2.8	158–183			
Sandstone		2.2–2.7	119–168	1.9–27.3		6–18
Quartzite			165–170	1.5–2.9		

TABLE 4.12 Permeability of Commercial Building Stones
[$in^3/(ft^2)(hr)$ *for ½-in thickness*]

Pressure, psi	1.2	50	100
Granite	0.06–0.08	0.11	0.28
Slate	0.006–0.008	0.08–0.11	0.11
Marble	0.06–0.35	1.3–16.8	0.9–28.0
Limestone	0.36–2.24	4.2–44.8	9.0–109
Sandstone	4.2–174.0	51.2	221

TABLE 4.13 Coefficient of Thermal Expansion of Commercial Building Stones

Stone	Range of coefficient
Limestone	$(4.2–22) \times 10^{-6}$
Marble	$(3.6–16) \times 10^{-6}$
Sandstone	$(5.0–12) \times 10^{-6}$
Slate	$(9.4–12) \times 10^{-6}$
Granite	$(6.3–9) \times 10^{-6}$

freezing and thawing the same marble for 30 cycles. Also, marble retains a permanent expansion after repeated heating.

4.25 FREEZING AND THAWING OF STONE

In freezing and thawing tests of 89 different marbles (''Physical and Chemical Tests of Commercial Marbles of U.S.,'' *U.S. National Bureau of Standards Technical Papers,* No. 123, Vol. 12), after 30 cycles, 66 marbles showed loss of strength ranging from 1.2 to 62.1% and averaging 12.3% loss. The other 23 marbles showed increases in strength ranging from 0.5 to 43.9% and averaging 11.2% increase.

Weight change was also determined in this investigation to afford another index of durability. Of 86 possible comparisons after 30 cycles of freezing and thawing, 16 showed no change in weight, 64 showed decreases in weight ranging from 0.01 to 0.28% and averaging 0.04% loss, while 6 showed increases in weight ranging from 0.01 to 0.08% and averaging 0.04%.

GYPSUM PRODUCTS

Gypsum is a cementitious material composed of at least 70% of $CaSO_4 \cdot 2H_2O$ by weight (Art. 4.6). It is a main ingredient of many building products.

4.26 GYPSUMBOARD

This product consists of a core of set gypsum surfaced with specifically manufactured paper firmly bonded to the core. It is designed to be used without addition of plaster for walls, ceilings, or partitions and provides a surface suitable to receive either paint or paper (see also Sec. 11). Gypsumboard is extensively used in ''drywall'' construction, where plaster is eliminated. It is also available with one surface covered with aluminum or other heat-reflecting type of foil, or with imitation woodgrain or other patterns on the exposed surface so that no additional decoration is required.

The types of gypsumboard generally available include wallboard, backing board, coreboard, fire-resistant gypsumboard, water-resistant gypsumboard, gypsum sheathing, and gypsum formboard.

Gypsum Wallboard. This type is used for the surface layer on interior walls and ceilings. Regular gypsum wallboard comes with gray liner paper on the back and a special paper covering, usually cream-colored, on facing side and edges. This covering provides a smooth surface suitable for decoration. Foil-backed gypsum wallboard has aluminum foil bonded to the liner paper to serve as a vapor barrier and, when contiguous to an airspace, as thermal insulation. Predecorated gypsum wallboard does not require decorative treatment after installation because it comes with a finished surface, often a decorative vinyl or paper sheet. Wallboard should conform with ASTM C36.

Wallboard usually is available 4 ft wide in the following thicknesses and lengths:

¼ in—for covering and rehabilitating old walls and ceilings, 4 to 12 ft long

⁵⁄₁₆ in—where thickness greater than ¼ in is desired, 4 to 14 ft long.

⅜ in—mainly for the outer face in two-layer wall systems, 4 to 16 ft long

½ in—for single-layer new construction with supports 16 to 24 in c to c, 4 to 16 ft long

⅝ in—for better fire resistance and sound control than ½ in provides, 4 to 16 ft long

Standard edges are rounded, beveled, tapered, or square.

Backing Board. This type is used as a base layer in multi-ply construction, where several layers of gypsumboard are desired for high fire resistance, sound control, and strength in walls. It has gray liner paper on front and back faces. Also available is backing board with aluminum foil bonded to the back face. Gypsum backing board should conform with ASTM C442. The boards come 16 to 48 in wide, 4 to 16 ft long, and ¼ to 1 in thick.

Gypsum Coreboard. To save space, this type is used as a base in multi-ply construction of self-supporting (studless) gypsum walls. Coreboard may be supplied as 1-in-thick, solid backing board or as two factory-laminated, ½-in-thick layers of backing board. Coreboard too should conform with C442.

Type X Gypsumboard. For use in fire-rated assemblies, Type X may be gypsum wallboard, backing board, or coreboard with core made more fire resistant by addition of glass fiber or other reinforcing materials.

Water-Resistant Gypsum Backing Board. This type comes with a water-resistant gypsum core and water-repellant face paper. It may be used as a base for wall tile in baths, showers, and other areas subject to wetting. The board should conform with ASTM C630.

Gypsum Sheathing. This type is used as fire protection and bracing of exterior frame walls. It must be protected from the weather by an exterior facing. Sheathing should conform with ASTM C79. It comes 24 to 48 in wide, 6 to 12 ft long, and ⅜, ⁴⁄₁₀, ½, and ⅝ in thick.

Gypsum Formboard. This type is used as a permanent form in the casting of gypsum-concrete roof decks.

(“Architect Data Book—Construction Products and Systems,” Gold Bond Building Products, a National Gypsum Division, 2001 Rexford Road, Charlotte, NC

28211; ‘‘Gypsum Products Design Data,’’ Gypsum Association, 1603 Orrington Ave., Evanston, IL 60201; ‘‘Gypsum Construction Handbook,’’ United States Gypsum, 101 South Wacker Drive, Chicago, IL 60606.)

4.27 GYPSUM LATH

Gypsum lath is similar to gypsumboard in that it consists of a core of set gypsum surfaced with paper. The paper for gypsumboard, however, is produced so that it is ready to receive paint or paper, while that for gypsum lath is specially designed or treated so that plaster will bond tightly to the paper. In addition, some lath provides perforations or other mechanical keying to assist in holding the plaster firmly on the lath. It is also available with reflective foil backing (see also Art. 11.25.5).

Gypsum lath should conform with ASTM C37. It comes in 16-, 16½-, 24-, and 32-in widths, lengths of 32, 36, and 48 in, and ⅜- and ½-in widths.

Veneers plasters, special proprietary compositions for thin plaster surfaces, are best applied over veneer plaster base, similar to gypsum lath, but produced to accommodate the veneer plaster compositions. Both gypsum lath and veneer base are made as regular, X-rated (fire-retardant), and insulating (foil-backed) types. These bases should conform with ASTM G588. They come 48 in wide, 6 to 16 ft long, and ⅜, ½, and ⅝ in thick.

4.28 GYPSUM SHEATHING BOARD

Gypsum sheathing boards are similar in construction to gypsumboard (Art. 4.26), except that they are provided with a water-repellent paper surface. They are commonly made ¾ to ⅝ in thick, 6 to 12 ft long, and with a nominal width of 24 or 48 in in conformance with ASTM C79. They are made with either square edges or with V tongue-and-groove edges. Sheathing boards also are available with a water-repellent core or fire-resistant Type X.

4.29 GYPSUM PARTITION TILE OR BLOCK

Gypsum tiles or blocks are used for non-load-bearing partition walls and for protection of columns, elevator shafts, etc., against fire. They have been essentially replaced by dry-wall systems.

4.30 GYPSUM PLANK

A precast gypsum product used particularly for roof construction is composed of a core of gypsum cast in the form of a plank, with wire-fabric reinforcement and usually with tongue-and-groove metal edges and ends. The planks are available in two thicknesses—a 2-in plank, which is 15 in wide and 10 ft long, and a 3-in plank which is 12 in wide and 30 in long. (See ASTM C377.)

GLASS AND GLASS BLOCK

Glass is so widely used for decorative and utilitarian purposes in modern construction that it would require an encyclopedia to list all the varieties available. Clear glass for windows and doors is made in varying thicknesses or strengths, also in double layers to obtain additional thermal insulation. Safety glass, laminated from sheets of glass and plastic, or made with embedded wire reinforcement, is available for locations where breakage might be hazardous. For ornamental work, glass is available in a wide range of textures, colors, finishes, and shapes.

4.31 WINDOW GLASS

Various types and grades of glass are used for glazing:

Clear Window Glass. This is the most extensively used type for windows in all classes of buildings. A range of grades, as established by Federal Government Standard DD-G-451c, classifies quality according to defects. The more commonly used grades are A and B. A is used for the better class of buildings where appearance is important, and B is used for industrial buildings, some low-cost residences, basements, etc.

With respect to thickness, clear window glass is classified as ‘‘single-strength’’ about 3⁄32 in thick; ‘‘double-strength,’’ about 1⁄8 in thick; and ‘‘heavy-sheet,’’ up to 7⁄32 in thick. Maximum sizes are as follows: single-strength, 40 × 50 in; double-strength, 60 × 80 in; and heavy sheet, 76 × 120 in. Because of flexibility, single strength and double strength should never be used in areas exceeding 12 ft^2, and for appearance’s sake areas should not exceed 7 ft^2.

Plate and Float Glass. These have, in general, the same performance characteristics. They are of superior quality, more expensive, and have better appearance, with no distortion of vision at any angle. Showcase windows, picture windows, and exposed windows in offices and commercial buildings are usually glazed with polished plate or float glass. Thicknesses range from 1⁄8 to 7⁄8 in. There are two standard qualities, *silvering* and *glazing,* the latter being employed for quality glazing.

Processed Glass and Rolled Figured Sheet. These are general classifications of obscure glass. There are many patterns and varying characteristics. Some provide true obscurity with a uniform diffusion and pleasing appearance, while others may give a maximum transmission of light or a smoother surface for greater cleanliness. The more popular types include a clear, polished surface on one side with a pattern for obscurity on the other side.

Obscure Wired Glass. This usually is specified for its fire-retarding properties, although it is also used in doors or windows where breakage is a problem. It should not be used in pieces over 720 in^2 in area (check local building code).

Polished Wired Glass. More expensive than obscure wired glass, polished wired glass is used where clear vision is desired, such as in school or institutional doors.

There are also many special glasses for specific purposes:

Heat-Absorbing Glass. This reduces heat, glare, and a large percentage of ultraviolet rays, which bleach colored fabrics. It often is used for comfort and reduction of air-conditioning loads where large areas of glass have a severe sun exposure. Because of differential temperature stresses and expansion induced by heat absorption under severe sun exposure, special attention should be given to edge conditions. Glass having clean-cut edges is particularly desirable, because these affect the edge strength, which, in turn must resist the central-area expansion. A resilient glazing material should be used.

Corrugated Glass, Wired Glass, and Plastic Panels. These are used for decorative treatments, diffusing light, or as translucent structural panels with color.

Laminated Glass. This consists of two or more layers of glass laminated together by one or more coatings or a transparent plastic. This construction adds strength. Some types of laminated glass also provide a degree of security, sound isolation, heat absorption, and glare reduction. Where color and privacy are desired, fadeproof opaque colors can be included. When fractured, a laminated glass tends to adhere to the inner layer of plastic and, therefore, shatters into small splinters, thus minimizing the hazard of flying glass.

Bullet-Resisting Glass. This is made of three or more layers of plate glass laminated under heat and pressure. Thicknesses of this glass vary from ¾ to 3 in. The more common thicknesses are 1³⁄₁₆ in, to resist medium-powered small arms: 1½ in, to resist high-powered small arms; and 2 in, to resist rifles and submachine guns. (Underwriters Laboratories lists materials having the required properties for various degrees of protection.) Greater thicknesses are used for protection against armor-piercing projectiles. Uses of bullet-resisting glass include cashier windows, bank teller cages, toll-bridge booths, peepholes, and many industrial and military applications. Transparent plastics also are used as bullet-resistant materials, and some of these materials have been tested by the Underwriters Laboratories. Thicknesses of 1¼ in or more have met UL standards for resisting medium-powered small arms.

Tempered Glass. This is produced by a process of reheating and sudden cooling that greatly increases strength. All cutting and fabricating must be done before tempering. Doors of ½- and ¾-in-thick tempered glass are commonly used for commercial building. Other uses, with thicknesses from ⅛ to ⅞ in, include backboards for basketball, showcases, balustrades, sterilizing ovens, and windows, doors, and mirrors in institutions. Although tempered glass is 4½ to 5 times as strong as annealed glass of the same thickness, it is breakable, and when broken, disrupts into innumerable small fragments of more or less cubical shape.

Tinted and Coated Glasses. These are available in several types and for varied uses. As well as decor, these uses can provide for light and heat reflection, lower light transmission, greater safety, sound reduction, reduced glare, and increased privacy.

Transparent Mirror Glass. This appears as a mirror when viewed from a brightly lighted side, and is transparent to a viewer on the darker opposite side. This one-way-vision glass is available as a laminate, plate or float, tinted, and in tempered quality.

Plastic Window Glazing. Made of such plastics as acrylic or polycarbonate, plastic glazing is used for urban school buildings and in areas where high vandalism might be anticipated. These plastics have substantially higher impact strength than glass or tempered glass. Allowance should be made in the framing and installation for expansion and contraction of plastics, which may be about 8 times as much as that of glass. Note also that the modulus of elasticity (stiffness) of plastics is about one-twentieth that of glass. Standard sash, however, usually will accommodate the additional thickness of plastic and have sufficient rabbet depth.

Suspended Glazing. This utilizes metal clamps bonded to tempered plate glass at the top edge, with vertical glass supports at right angles for resistance to wind pressure (Fig. 4.1). These vertical supports, called stabilizers, have their exposed edges polished. The joints between the large plates and the stabilizers are sealed with a bonding cement. The bottom edge or sill is held in position by a metal channel, and sealed with resilient waterproofing. Suspended glazing offers much greater latitude in use of glass and virtually eliminates visual barriers.

Safety Glazing. A governmental specification Z-97, adopted by many states, requires entrance-way doors and appurtenances glazed with tempered, laminated, or plastic material.

4.32 GLASS BLOCK

Glass blocks are made by first pressing or shaping half blocks to the desired form, then fusing the half blocks to form a complete block. A block is usually 3⅞ in thick and 5¾, 7¾, or 11¾ in square. The center of the block is hollow and is under a partial vacuum, which adds to the insulating properties of the block. Corner and radial blocks are also available to produce desired architectural effects.

Glass block is commonly laid up in a cement or a cement-lime mortar. Since there is no absorption by the block to facilitate bond of mortar, various devices are employed to obtain a mechanical bond. One such device is to coat the sides of the block with a plastic and embed therein particles of sand. The difficulty in obtaining permanent and complete bond sometimes leads to the opening up of mortar joints. A wall of glass block, exposed to the weather, may leak badly in a rainstorm unless unusual precautions have been taken during the setting of the block to obtain full and complete bond.

Glass blocks have a coefficient of thermal expansion that is from 1½ to 2 times that of other masonry. For this reason, large areas of block may expand against solid masonry and develop sufficient stress so that the block will crack. Manufacturers usually recommend an expansion joint every 10 ft or so, to prevent building up of pressure sufficient to crack the block. With adequate protection against expansion and with good workmanship, or with walls built in protected locations,

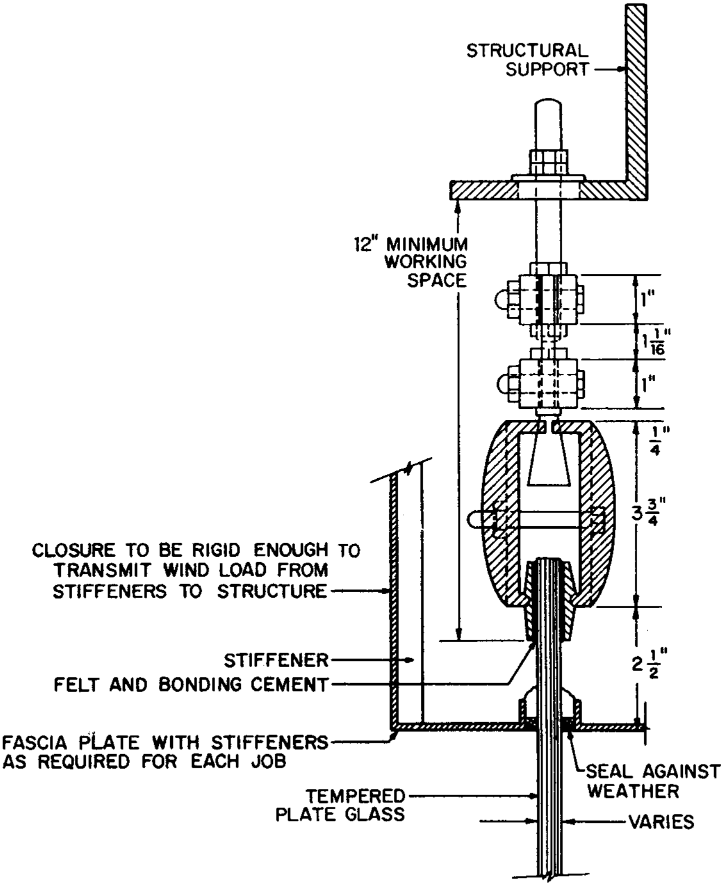

FIGURE 4.1 Typical details of suspended glazing. (*F. H. Sparks, Co., Inc., New York.*)

glass-block walls are ornamental, sanitary, excellent light transmitters, and have rather low thermal conductivity.

WOOD

Wood is a building material made from trees. It is a natural polymer composed of cells in the shape of long, thin tubes with tapered ends. The cell wall consists of cellulose crystals, which are bonded together by a complex amorphous lignin composed of carbohydrates. Most of the cells in a tree trunk are oriented vertically. Consequently, properties of wood in the direction of cell axes, usually referred to

TABLE 4.14 Strength of Some Commercially Important Woods Grown in the United States* (Results of Tests on Small, Clear Specimens†)

Commercial name of species	Specific gravity	Modulus of		Compression parallel to grain, maximum crushing strength, psi	Compression perpendicular to grain, fiber stress at proportional limit, psi	Shear parallel to grain, maximum shearing strength, psi	Side hardness, load perpendicular to grain, lb
		Rupture, ksi	Elasticity, ksi				
Ash, white	0.55	9.6	1440	3,900	670	1380	960
	0.60	15.4	1740	7,410	1160	1950	1320
Beech, American	0.56	8.6	1380	3,550	540	1290	850
	0.64	14.9	1720	7,300	1010	2010	1300
Birch, yellow	0.55	8.3	1500	3,380	430	1110	780
	0.62	16.6	2010	8,170	970	1880	1260
Cedar, western red	0.31	5.2	940	2,770	240	770	260
	0.32	7.5	1110	4,560	460	990	350
Chestnut, American	0.40	5.6	930	2,470	310	800	420
	0.43	8.6	1230	5,230	620	1080	540
Cypress, bald	0.42	6.6	1180	3,580	400	810	390
	0.46	10.6	1440	6,360	730	1000	510
Douglas fir, coast	0.45	7.7	1560	3,780	380	900	500
	0.48	12.4	1950	7,240	800	1130	710
Douglas fir, interior, west	0.46	7.7	1510	3,870	420	940	510
	0.50	12.6	1820	7,440	760	1290	660
Elm, American	0.46	7.2	1110	2,910	360	1000	620
	0.50	11.8	1340	5,520	690	1510	830
Hemlock, eastern	0.38	6.4	1070	3,080	360	850	400
	0.40	8.9	1200	5,410	650	1060	500
Hemlock, western	0.42	6.6	1310	3,360	280	860	410
	0.45	11.3	1640	7,110	550	1250	540
Hickory, pecan	0.60	9.8	1370	3,990	780	1480	1310
	0.66	13.7	1730	7,850	1720	2080	1820

TABLE 4.14 Strength of Some Commercially Important Woods Grown in the United States* (Continued)
(Results of Tests on Small, Clear Specimens†)

		Modulus of					
Commercial name of species	Specific gravity	Rupture, ksi	Elasticity, ksi	Compression parallel to grain, maximum crushing strength, psi	Compression perpendicular to grain, fiber stress at proportional limit, psi	Shear parallel to grain, maximum shearing strength, psi	Side hardness, load perpendicular to grain, lb
Locust, black	0.66	13.8	1850	6,800	1160	1760	1570
	0.69	19.4	2050	10,180	1830	2480	1700
Larch, western	0.48	4.9	960	3,760	400	870	510
	0.52	13.1	1870	7,640	930	1360	830
Maple, sugar	0.56	9.4	1550	4,020	640	1460	970
	0.63	15.8	1830	7,830	1470	2330	1450
Oak, northern red	0.56	8.3	1350	3,440	610	1210	1000
	0.63	14.3	1820	6,760	1010	1780	1290
Oak, white	0.60	8.3	1250	3,560	670	1250	1060
	0.68	15.2	1780	7,440	1070	2000	1360
Pine shortleaf	0.47	7.4	1390	3,530	350	910	440
	0.51	13.1	1750	7,270	820	1390	690
Pine, longleaf	0.54	8.5	1590	4,320	480	1040	590
	0.59	14.5	1980	8,470	960	1510	870
Pine, sugar	0.34	4.9	1030	2,460	210	720	270
	0.36	8.2	1190	4,460	500	1130	380
Pine, western white	0.35	4.7	1190	2,430	190	680	260
	0.38	9.7	1460	5,040	470	1040	420
Yellow poplar	0.40	6.0	1220	2,660	270	790	440
	0.42	10.1	1580	5,540	500	1190	540
Redwood, old growth	0.38	7.5	1180	4,200	420	800	410
	0.40	10.0	1340	6,150	700	940	480
Spruce, white	0.37	5.6	1070	2,570	240	690	320
	0.40	9.8	1340	5,470	460	1080	480
Tupelo, black	0.46	7.0	1030	3,040	480	1100	640
	0.50	9.6	1200	5,520	930	1340	810

*From U.S. Forest Products Laboratory.

†Values in first line are for green material. Values in second line are adjusted to 12% moisture content.

as longitudinal, or parallel to grain, differ from those in the other (radial or circumferential) directions, or across the grain.

4.33 MECHANICAL PROPERTIES OF WOOD

Because of its structure, wood has different strength properties parallel and perpendicular to the grain. Tensile, bending, and compressive strengths are greatest parallel to the grain and least across the grain, whereas shear strength is least parallel to the grain and greatest across the grain. Except in plywood, the shearing strength of wood is usually governed by the parallel-to-grain direction.

The compressive strength of wood at an angle other than parallel or perpendicular to the grain is given by the following formula:

$$C_\theta = \frac{C_2 C_2}{C_1 \sin^2 \theta + C_2 \cos^2 \theta} \tag{4.2}$$

in which C_θ is the strength at the desired angle θ with the grain, C_1 is the compressive strength parallel to grain, and C_2 is the compressive strength perpendicular to the grain.

Increasing moisture content reduces all strength properties except impact bending, in which green wood is stronger than dry wood. The differences are brought out in Table 4.14. In practice, no differentiation is made between the strength of green and dry wood in engineering timbers, because of seasoning defects that may occur in timbers as they dry and because large timbers normally are put into service without having been dried. This is not true of laminated timber, in which dry wood must be employed to obtain good glued joints. For laminated timber, higher stresses can be employed than for ordinary lumber. In general, compression and bending parallel to the grain are affected most severely by moisture, whereas modulus of elasticity, shear, and tensile strength are affected less. In practice, tensile strength parallel to the grain is taken equal to the bending strength of wood.

In Table 4.14 are summarized also the principal mechanical properties of the most important American commercial species.

Values given in the table are average ultimate strengths. To obtain working stresses from these, the following must be considered: (1) Individual pieces may vary 25% above and below the average. (2) Values given are for standard tests that are completed in a few minutes. Over a period of years, however, wood may fail under a continuous load about 9⁄16 that sustained in a standard test. (3) The modulus of rupture of a standard 2-in-deep flexural-test specimen is greater than that of a deep beam. In deriving working stresses, therefore, variability, probable duration of load, and size are considered, and reduction factors are applied to the average ultimate strengths to provide basic stresses, or working stresses, for blemishless lumber. These stresses are still further reduced to account for such blemishes as knots, wane, slope of grain, shakes, and checks, to provide working stresses for classes of commercial engineering timbers. (See Sec. 10 for engineering design in timber.)

4.34 EFFECTS OF HYGROSCOPIC PROPERTIES OF WOOD

Because of its nature, wood tends to absorb moisture from the air when the relative humidity is high, and to lose it when the relative humidity is low. Moisture imbibed into the cell walls causes the wood to shrink and swell as the moisture content changes with the relative humidity of the surrounding air. The maximum amount of imbibed moisture the cell walls can hold is known as the fiber-saturation point, and for most species is in the vicinity of 25 to 30% of the oven-dry weight of the wood. Free water held in the cell cavities above the fiber-saturation point has no effect upon shrinkage or other properties of the wood. Changes in moisture content below the fiber-saturation point cause negligible shrinkage or swelling along the grain, and such shrinkage and swelling are normally ignored; but across the grain, considerable shrinkage and swelling occur in both the radial and tangential direction. Tangential shrinkage (as in flat-cut material) is normally approximately 50% greater than radial shrinkage (as in edge-grain material). See also Art. 10.1.

Separation of grain, or checking, is the result of rapid lowering of surface moisture content combined with a difference in moisture content between inner and outer portions of the piece. As wood loses moisture to the surrounding atmosphere, the outer cells of the member lose at a more rapid rate than the inner cells. As the outer cells try to shrink, they are restrained by the inner portion of the member. The more rapid the drying, the greater will be the differential in shrinkage between outer and inner fibers, and the greater the shrinkage stresses. As a result, checks may develop into splits.

Checks are radial cracks caused by nonuniform drying of wood. A **split** is a crack that results from complete separation of the wood fibers across the thickness of a member and extends parallel to the grain. (**Shakes** are another type of defect. Usually parallel to an annular ring, they develop in standing trees, whereas checks and splits are seasoning defects.) Lumber grading rules limit these types of defects.

Checks affect the horizontal shear strength of timber. A large reduction factor is applied to test values in establishing design values, in recognition of stress concentrations at the ends of checks. Design values for horizontal shear are adjusted for permissible checking in the various stress grades at the time of the grading. Since strength properties of wood increase with dryness, checks may enlarge with increasing dryness after shipment, without appreciably reducing shear strength.

Cross-grain checks and splits that tend to run out the side of a piece, or excessive checks and splits that tend to enter connection areas, may be serious and may require servicing. Provisions for controlling the effects of checking in connection areas may be incorporated in design details.

To avoid excessive splitting between rows of bolts caused by shrinkage during seasoning of solid-sawn timbers, rows should not be spaced more than 5 in apart, or a saw kerf, terminating in a bored hole, should be provided between lines of bolts. Whenever possible, maximum end distances for connections should be specified to minimize the effect of checks running into the joint area. Some designers requires stitch bolts in members, with multiple connections loaded at an angle to the grain. Stitch bolts, kept tight, will reinforce pieces where checking is excessive.

One of the principal advantages of glued-laminated timber construction is relative freedom from checking. Seasoning checks may, however, occur in laminated members for the same reasons that they exist in solid-sawn members. When laminated members are glued within the typical range of moisture contents of 7 to 16% for the laminating lumber at the time of gluing, they will approximate the moisture content in normal-use conditions, thereby minimizing checking. Moisture content of the lumber at the time of gluing is thus of great importance to the control of checking in service. However, rapid changes in moisture content of large wood sections after gluing will result in shrinkage or swelling of the wood, and during shrinking, checking may develop in both glued joints and wood.

Differentials in shrinkage rates of individual laminations tend to concentrate shrinkage stresses at or near the glue line. For this reason, when checking occurs, it is usually at or near glue lines. The presence of wood-fiber separation indicates adequate glue bonds, and not delamination.

In general, checks have very little effect on the strength of glued-laminated members. Laminations in such members are thin enough to season readily in kiln drying without developing checks. Since checks lie in a radial plane, and the majority of laminations are essentially flat grain, checks are so positioned in horizontally laminated members that they will not materially affect shear strength. When members are designed with laminations vertical (with wide face parallel to the direction of load application), and when checks may affect the shear strength, the effect of checks may be evaluated in the same manner as for checks in solid-sawn members.

Seasoning checks in bending members affect only the horizontal shear strength (Art. 10.5.13). They are usually not of structural importance unless the checks are significant in depth and occur in the midheight of the member near the support, and then only if shear governs the design of the members. The reduction in shear strength is nearly directly proportional to the ratio of depth of check to width of beam. Checks in columns are not of structural importance unless the check develops into a split, thereby increasing the slenderness ratio of columns.

Minor checking may be disregarded, since there is ample safety factor in allowable design values. The final decision as to whether shrinkage checks are detrimental to the strength requirements of any particular design or structural member should be made by a competent engineer experienced in timber construction.

4.35 COMMERCIAL GRADES OF WOOD

Lumber is graded by the various associations of lumber manufacturers having jurisdiction over various species. Two principal sets of grading rules are employed: (1) for softwoods, and (2) for hardwoods.

Softwoods. Softwood lumber is classified as dry, moisture content 19% or less; and green, moisture content above 19%.

According to the American Softwood Lumber Standard, softwoods are classified according to use as:

Yard Lumber. Lumber of grades, sizes, and patterns generally intended for ordinary construction and general building purposes.

Structural Lumber. Lumber 2 in or more nominal thickness and width for use where working stresses are required.

Factory and Shop Lumber. Lumber produced or selected primarily for manufacturing purposes.

Softwoods are classified according to extent of manufacture as:

Rough Lumber. Lumber that has not been dressed (surfaced) but has been sawed, edged, and trimmed.

Dressed (*Surfaced*) *Lumber.* Lumber that has been dressed by a planning machine (for the purpose of attaining smoothness of surface and uniformity of size) on one side (S1S), two sides (S2S), one edge (S1E), two edges (S2E), or a combination of sides and edges (S1S1E, S1S2, S2S1E, S4S).

Worked Lumber. Lumber that, in addition to being dressed, has been matched, shiplapped or patterned:

Matched Lumber. Lumber that has been worked with a tongue on one edge of each piece and a groove on the opposite edge.

Shiplapped Lumber. Lumber that has been worked or rabbeted on both edges, to permit formation of a close-lapped joint.

Patterned Lumber. Lumber that is shaped to a pattern or to a molded form.

Softwoods are also classified according to nominal size:

Boards. Lumber less than 2 in in nominal thickness and 2 in or more in nominal width. Boards less than 6 in in nominal width may be classified as strips.

Dimension. Lumber from 2 in to, but not including, 5 in in nominal thickness, and 2 in or more in nominal width. Dimension may be classified as framing, joists, planks, rafters, studs, small timbers, etc.

Timbers. Lumber 5 in or more nominally in least dimension. Timber may be classified as beams, stringers, posts, caps, sills, girders, purlins, etc.

Actual sizes of lumber are less than the nominal sizes, because of shrinkage and dressing. In general, dimensions of dry boards, dimension lumber, and timber less than 2 in wide or thick are ¼ in less than nominal; from 2 to 7 in wide or thick, ½ in less, and above 6 in wide or thick, ¾ in less. Green-lumber less than 2 in wide or thick is 1⁄32 in more than dry; from 2 to 4 in wide or thick, 1⁄16 in more, 5 and 6 in wide or thick, ⅛ in more, and 8 in or above in width and thickness, ¼ in more than dry lumber. There are exceptions, however.

Yard lumber is classified on the basis of quality as:

Appearance. Lumber is good appearance and finishing qualities, often called *select.*

Suitable for natural finishes
  Practically clear
  Generally clear and of high quality
Suitable for paint finishes
  Adapted to high-quality paint finishes
  Intermediate between high-finishing grades and common grades, and partaking somewhat of the nature of both

Common. Lumber suitable for general construction and utility purposes, often given various commercial designations.

For standard construction use
  Suitable for better-type construction purposes
  Well adapted for good standard construction
  Designed for low-cost temporary construction
For less exacting purposes
  Low quality, but usable

Structural lumber is assigned modulus of elasticity values and working stresses in bending, compression parallel to grain, compression perpendicular to grain, and horizontal shear in accordance with ASTM procedures. These values take into account such factors as sizes and locations of knots, slope of grain, wane, and shakes or checks, as well as such other pertinent features as rate of growth and proportions of summerwood.

Factory and shop lumber is graded with reference to its use for doors and sash, or on the basis of characteristics affecting its use for general cut-up purposes, or on the basis of size of cutting. The grade of factory and shop lumber is determined by the percentage of the area of each board or plank available in cuttings of specified or of given minimum sizes and qualities. The grade of factory and shop lumber is determined from the poor face, although the quality of both sides of each cutting must be considered.

Hardwoods. Because of the great diversity of applications for hardwood both in and outside the construction industry, hardwood grading rules are based on the proportion of a given piece that can be cut into smaller pieces of material clear on one or both sides and not less than a specified size. Grade classifications are therefore based on the amount of clear usable lumber in a piece.

Special grading rules of interest in the construction industry cover hardwood interior trim and moldings, in which one face must be practically free of imperfections and in which Grade A may further limit the amount of sapwood as well as stain. Hardwood dimension rules, in addition, cover clears, which must be clear both faces; clear one face; paint quality, which can be covered with pain; core, which must be sound on both faces and suitable for cores of glued-up panels; and sound, which is a general-utility grade.

Hardwood flooring is graded under two separate sets of rules: (1) for maple, birch, and beech; and (2) for red and white oak and pecan. In both sets of rules, color and quality classifications range from top-quality to the lower utility grades. Oak may be further subclassified as quarter-sawed and plain-sawed. In all grades, top-quality material must be uniformed in color, whereas other grades place no limitation on color.

Shingles are graded under special rules, usually into three classes: Number 1, 2, and 3. Number 1 must be all edge grain and strictly clear, containing no sapwood. Numbers 2 and 3 must be clear to a distance far enough away from the butt to be well covered by the next course of shingles.

4.36 DESTROYERS AND PRESERVATIVES

The principal destroyers of wood are decay, caused by fungus, and attack by a number of animal organisms of which termites, carpenter ants, grubs of a wide variety of beetles, teredo, and limnoria are the principal offenders. In addition, fire annually causes widespread destruction of wood structures.

Decay will not occur if wood is kept well ventilated and air-dry or, conversely, if it is kept continuously submerged so that air is excluded.

Most termites in the United States are subterranean and require contact with the soil. The drywood and dampwood termites found along the southern fringes of the country and along the west coast, however, do not require direct soil contact and are more difficult to control.

Teredo, limnoria, and other water-borne wood destroyers are found only in salt or brackish waters.

Various wood species vary in natural durability and resistance to decay and insect attack. The sapwood of all species is relatively vulnerable; only the heartwood can be considered to be resistant. Table 4.15 lists the common species in accordance with heartwood resistance. Such a list is only approximate, and individual pieces deviate considerably.

Preservatives employed to combat the various destructive agencies may be subdivided into oily, water-soluble salts, and solvent-soluble organic materials. The principal oily preservatives are coal-tar creosote and creosote mixed with petroleum.

TABLE 4.15 Resistance to Decay of Heartwood of Domestic Woods

Resistant or very resistant	Moderately resistant	Slightly or nonresistant
Baldcypress (old growth)*	Baldcypress (young growth)*	Alder
Catalpa	Douglas fir	Ashes
Cedars	Honeylocust	Aspens
Cherry, black	Larch, western	Basswood
Chestnut	Oak, swamp chestnut	Beech
Cypress, Arizona	Pine, eastern white*	Birches
Junipers	Souther pine:	Buckeye
Locust, black†	Longleaf*	Butternut
Mesquite	Slash*	Cottonwood
Mulbery, red†	Tamarack	Elms
Oak:		Hackberry
Bur		Hemlocks
Chesnut		Hickories
Gambel		Magnolia
Orgeon white		Maples
Post		Oak (red and black species)
White		Pines (other than longleaf, slash, and eastern white)
Osage orange†		Poplars
Redwood		Spruces
Sassafras		Sweetgum
Walnut, black		True firs (western and eastern)
Yew, Pacific†		Willows
		Yellow poplar

* The southern and eastern pines and baldcypress are now largely second growth with a large proportion of sapwood. Consequently, substantial quantities of heartwood lumber of these species are not available.

† These woods have exceptionally high decay resistance.

From U.S. Forest Products Laboratory.

The most commonly employed water-soluble salts are acid copper chromate, chromated copper arsenate and arsenite, fluor chrome arsenate phenol, chromated zinc chloride, and other materials that are often sold under various proprietary names. The principal solvent-soluble organic materials are chlorinated phenols, such as pentachlorphenol, and copper naphthenate.

Preservatives may be applied in a variety of ways, including brushing and dipping, but for maximum treatment, pressure is required to provide deep side-grain penetration. Butts of poles and other parts are sometimes placed in a hot boiling creosote or salt solution, and after the water in the wood has been converted to steam, they are quickly transferred to a cold vat of the same preservative. As the steam condenses, it produces a partial vacuum, which draws the preservative fairly deeply into the surface.

Pressure treatments may be classified as full-cell and empty-cell. In the full-cell treatment, a partial vacuum is first drawn in the pressure-treating tank to withdraw most of the air in the cells of the wood. The preservative is then let in without breaking the vacuum, after which pressure is applied to the hot solution. After treatment is completed, the individual cells are presumably filled with preservative. In the empty-cell method, no initial vacuum is drawn, but the preservative is pumped in under pressure against the back pressure of the compressed air in the wood. When the pressure is released, the air in the wood expands and forces out excess preservative, leaving only a coating of preservative on the cell walls.

Retentions of preservative depend on the application. For teredo-infestation, full-cell creosote treatment to refusal may be specified, ranging from 16 to 20 lb per cubic foot of wood. For ordinary decay conditions and resistance to termites and other destroyers of a similar nature, the empty-cell method may be employed with retentions in the vicinity of 6 to 8 lb of creosote per cubic foot of wood. Salt retentions generally range in the vicinity of 1½ to 3 lb of dry salt retained per cubic food of wood.

Solvent-soluble organic materials, such as pentachlorphenol, are commonly employed for the treatment of sash and door parts to impart greater resistance to decay. This is commonly done by simply dipping the parts in the solution and then allowing them to dry. As the organic solvent evaporates, it leaves the water-insoluble preservative behind in the wood.

These organic materials are also employed for general preservative treatment, including fence posts and structural lumber. The water-soluble salts and solvent-soluble organic architects leave the wood clean and paintable. Creosote in general cannot be painted over, although partial success can be achieved with top-quality aluminum-flake pigment paints.

Treatment against fire consists generally of applying salts containing ammonium and phosphates, of which monoammonium phosphate and diammonium phosphate are widely employed. At retentions of 3 to 5 lb of dry salt per cubic foot, the wood does not support its own combustion, and the afterglow when fire is removed is short. A variety of surface treatments is also available, most of which depend on the formation of a blanket of inert-gas bubbles over the surface of the wood in the presence of flame or other sources of heat. The blanket of bubbles insulates the wood beneath and retards combustion.

See also Art. 10.6.

4.37 GLUES AND ADHESIVES FOR WOOD

A variety of adhesives is now available for use with wood, depending on the final application. The older adhesives include animal glue, casein glue, and a variety of vegetable glues, of which soybean is today the most important. Animal glues provide strong, tough, easily made joints, which, however, are not moisture-resistant. Casein mixed with cold water, when properly formulated, provides highly moisture-resistant glue joints, although they cannot be called waterproof. The vegetable glues have good dry strength but are not moisture-resistant.

The principal high-strength glues today are synthetic resins, of which phenol formaldehyde, urea formaldehyde, resorcinol formaldehyde, melamine formaldehyde, and epoxy are the most important. Phenol, resorcinol, and melamine provide glue joints that are completely waterproof and will not separate when properly made even on boiling. Urea formaldehyde provides a glue joint of high moisture resistance, although not quite so good as the other three. Phenol and melamine require application of heat, as well as pressure, to cure the adhesive. Urea and resorcinol, however, can be formulated to be mixed with water at ordinary temperatures and hardened without application of heat above room temperature. Waterproof plywood is commonly made in hot-plate presses with phenolic or melamine adhesive. Resorcinol is employed where heat cannot be applied, as in a variety of assembly operations and the manufacture of laminated parts like ships' keels, which must have the maximum in waterproof qualities. Epoxide resins provide strong joints. Adhesives containing an elastomeric material, such as natural or synthetic rubber, may be classified as contact or mastic. The former, applied to both mating surfaces and allowed to partly dry, permit adhesion on contact. Mastics are very viscous and applied with a trowel or putty knife. They may be used to set wood-block flooring.

An emulsion of polyvinyl acetate serves as a general-purpose adhesive, for general assembly operations where maximum strength and heat or moisture resistance are not required. This emulsion is merely applied to the surfaces to be bonded, after which they are pressed together and the adhesive is allowed to harden.

4.38 PLYWOOD AND OTHER FABRICATED WOOD BOARDS

As ordinarily made, plywood consists of thin sheets, or veneers, of wood glued together. The grain is oriented at right angles in adjacent plies. To obtain plywood with balance—that is, which will not warp, shrink, or twist unduly—the plies must be carefully selected and arranged to be mirror images of each other with respect to the central plane. The outside plies or faces are parallel to each other and are of species that have the same shrinkage characteristics. The same holds true of the cross bands. As a consequence, plywood has an odd number of plies, the minimum being three.

Principal advantages of plywood over lumber are its more nearly equal strength properties in length and width, greater resistance to checking, greatly reduced shrinkage and swelling, and resistance to splitting.

The approach to equalization of strength of plywood in the various directions is obtained at the expense of strength in the parallel-to-grain direction; i.e., plywood is not so strong in the direction parallel to its face plies as lumber is parallel to the grain. But plywood is considerably stronger in the direction perpendicular to its face plies than wood is perpendicular to the grain. Furthermore, the shearing strength of plywood in a plane perpendicular to the plane of the plywood is very much greater than that of ordinary wood parallel to the grain. In a direction parallel to the plane of the plywood, however, the shearing strength of plywood is less than that of ordinary wood parallel to the grain, because in this direction rolling shear occurs in the plywood; i.e., the fibers in one ply tend to roll rather than to slide.

Depending on whether plywood is to be used for general utility or for decorative purposes, the veneers employed may be cut by peeling from the log, by slicing, or today very rarely, by sawing. Sawing and slicing give the greatest freedom and versatility in the selection of grain. Peeling provides the greatest volume and the most rapid production, because logs are merely rotated against a flat knife and the veneer is peeled off in a long continuous sheet.

Plywood is classified as interior or exterior, depending on the type of adhesive employed. Interior-grade plywood must have a reasonable degree of moisture resistance but is not considered to be waterproof. Exterior-grade plywood must be completely waterproof and capable of withstanding immersion in water or prolonged exposure to outdoor conditions.

In addition to these classifications, plywood is further subclassified in a variety of ways depending on the quality of the surface ply. Top quality is clear on one or both faces, except for occasional patches. Lower qualities permit sound defects, such as knots and similar blemishes, which do not detract from the general utility of the plywood but detract from its finished appearance.

Particle Board. Wood chips, sawdust, and flakes are pressed with a binder (urea-formaldehyde or phenol-formaldehyde) to form boards (sheathing, underlayment, corestock), having uniform strength and low shrinkage in the plane of the board.

Hardboard. Wood chips (exploded by high-pressure steam into wood fibers) and lignin are pressed to form boards of various densities. Additives may add weather resistance and other properties.

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STEEL AND STEEL ALLOYS

Iron and its alloys are generally referred to as **ferrous metals.** Even small amounts of alloy change the properties of ferrous metals significantly. Also, the properties can be changed considerably by changing the atomic structure of these metals by heating and cooling.

4.40 TYPES OF IRONS AND STEELS

Steel is a solution of carbon in iron. Various types of steel are produced by varying the percentage of carbon added to molten iron and controlling the cooling, which affects the atomic structure of the product, and hence its properties. Some of the structural changes can be explained with the aid of an iron-carbon equilibrium diagram (Fig. 4.2).

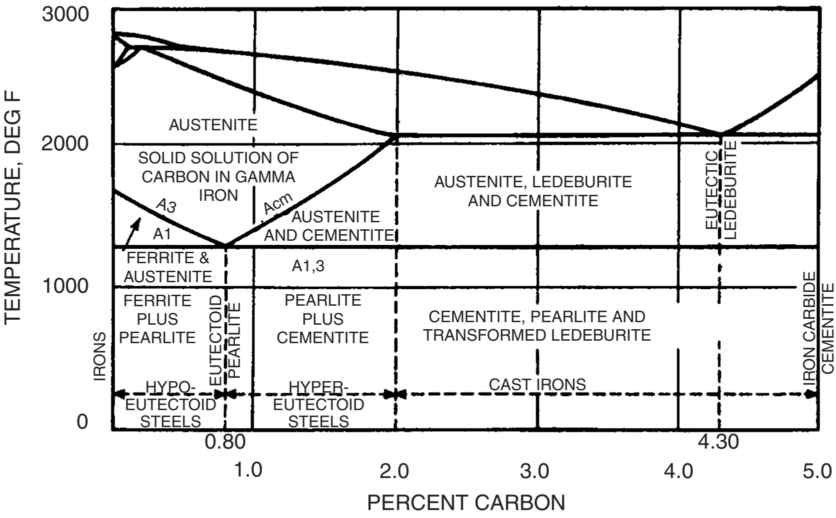

FIGURE 4.2 Iron-carbon diagram.

4.40.1 Iron-Carbon Equilibrium Diagram

The iron-carbon equilibrium diagram in Fig. 4.2 shows that, under equilibrium conditions (slow cooling) if not more than 2.0% carbon is present, a solid solution of carbon in gamma iron exists at elevated temperatures. This is called austenite. If the carbon content is less than 0.8%, cooling below the A_3 temperature line causes transformation of some of the austenite to ferrite, which is substantially pure alpha iron (containing less than 0.01% carbon in solution). Still further cooling to below the A_1 line causes the remaining austenite to transform to pearlite—the eutectoid mixture of fine plates, or lamellas, of ferrite and cementite (iron carbide) whose iridescent appearance under the microscope gives it its name.

If the carbon content is 0.8%, no transformation on cooling the austenite occurs until the A_1 temperature is reached. At that point, all the austenite transforms to pearlite, with its typical “thumbprint” microstructure.

At carbon contents between 0.80 and 2.0%, cooling below the A_{cm} temperature line causes iron carbide, or cementite, to form in the temperature range between A_{cm} and $A_{1,3}$. Below $A_{1,3}$, the remaining austenite transforms to pearlite.

4.40.2 Types of Irons

Metals containing substantially no carbon (several hundredths of 1%) are called irons, of which wrought iron, electrolytic iron, and “ingot” iron are examples.

Wrought iron, whether made by the traditional puddling method or by mixing very low carbon iron and slag, contains a substantial amount of slag. Because it contains very little carbon, it is soft, ductile, and tough and, like low-carbon ferrous metals generally, is relatively resistant to corrosion. It is easily worked. When broken, it shows a fibrous fracture because of the slag inclusions. “Ingot” iron is a very low carbon iron containing no slag, which is also soft, ductile, and tough.

TABLE 4.16 ASTM Requirements for Structural, Reinforcing, and Fastening Steels*

	ASTM specification	Tensile strength, min, ksi†	Yield point, min, ksi†	Elongation in 8 in, min, %	Elongation in 2 in, min, %‡	Bend test, ratio of bend diameter, in, to specimen thickness, in§				
						0–¾	¾–1	1–1½	1½–2	Over 2
Structural steel	A36	58–80	36	20	23–21	½	1	1½	2½	3
Welded or seamless pipe	A53	45–60	25–35							
High-strength, low-alloy, structural steel	A242	63–70	42–50	18	21	1	1½	2	2½	3
High-strength, low-alloy columbium-vanadium steels	A572	60–80	42–65	20–15	24–17	Depends on grade*				
High-strength, low-alloy structural steel	A588	63–70	42–50	18	21	1	1½	2	2½	3
High-yield-strength, quenched and tempered alloy steel	A514	110–130	90–100		17–18	2	2	3	4	4
Structural steel	A529	60–85	42	19		1				
High-strength, quenched and tempered alloy steel	A852	90–110	70	19						
Normalized high-strength low-alloy steel	A633	63–100	42–60	18	23	2	2	2½	2½	3
Quenched and tempered steel plate	A678	70–110	50–75		22–18	1–2	2–3	2–3	2½–3	2–2½
Cold-formed, welded and seamless tubing	A500	45–62	33–46		25–14					
Hot-formed, welded and seamless tubing	A501	58	36	20	23					
High-strength steel bolts	A325	105	81		14					

TABLE 4.16 ASTM Requirements for Structural, Reinforcing, and Fastening Steels* (Continued)

	ASTM specification	Tensile strength, min, ksi†	Yield point, min, ksi†	Elongation in 8 in, min, %	Elongation in 2 in, min, %‡	Bend test, ratio of bend diameter, in, to specimen thickness, in§				
						0–¾	¾–1	1–1½	1½–2	Over 2
High-strength, alloy steel bolts	A490	150–170	115–130		14					
Bolts and nuts, machine	A307	60–100			18					
Sheetpiling	A328	70	39	17		2				
Cast steel, 65–35, annealed	A27	60–70	30–40		22–24					
High-strength cast steel, 80–50	A148	80–260	40–210		18–3					
						180° bend test; ratio of pin diameter to specimen diameter				
Reinforcing steel for concrete:										
Billet-steel bars	A615					Under No. 6: 4; Nos. 6, 7, 8, 9, 10, 11: 5				
Grade 40		70	40	7–11						
Grade 60		90	60	7–9		Under No. 6: 4; No. 6: 5; Nos. 7, 8: 6; Nos. 9, 10, 11: 8				
Rail-steel bars	A616									
Grade 50		80	50	5–6		Under No. 8: 6; Nos. 9, 10, 11: 8¶				
Grade 60		90	60	4.5–6		Under No. 8: 6; Nos. 9, 10, 11: 8¶				

* The following are appropriate values for all the steels:
Modulus of elasticity—29,000 ksi
Shear modulus—11,000 ksi
Poisson's ratio—0.30
Yield stress in shear—$0.57F_t$, where F_t = tensile stress
Ultimate strength in shear—$0.67F_t$ to $0.75F_t$
Coefficient of thermal expansion—0.0000065 in/in · °F for temperatures between −60 and 150°F
Density—490 lb/ft^3

† Where two values are given, the first is the minimum and the second is the maximum. See the relevant specification for the values for each grade and applicable thicknesses.

‡ The minimum elongations are modified for some thicknesses in accordance with the specification for the steel.

§ Optional. See ASTM A6, "General Requirements for Rolled Steel Plates, Shapes, Sheet Piling, and Bars for Structural Use."

¶ 90° bend for No. 11 bars.

Above 2.0% carbon content is the region of the cast irons. Above the $A_{1,3}$ temperature, austenite, the eutectic ledeburite and cementite occur; below the $A_{1,3}$ temperature, the austenite transforms to pearlite, and a similar transformation of the ledeburite occurs.

When the silicon content is kept low, and the metal is cooled rapidly, **white cast iron** results. It is hard and brittle because of the high cementite content. White cast iron as such has little use; but when it is reheated and held a long time in the vicinity of the transformation temperature, then cooled slowly, the cementite decomposes to ferrite and nodular or temper carbon. The result is black-heart **malleable iron.** If the carbon is removed during malleabilization, white-heart malleable iron results.

If the silicon content is raised, and the metal is cooled relatively slowly, **gray cast iron** results. It contains cementite, pearlite, ferrite, and some free carbon, which gives it its gray color. Gray iron is considerably softer and tougher than white cast iron and is generally used for castings of all kinds. Often, it is alloyed with elements like nickel, chromium, copper, and molybdenum.

At 5.0% carbon, the end products is hard, brittle iron carbide or cementite.

4.40.3 Types of Carbon Steels

Most of the steel used for construction is low- to medium-carbon, relatively mild, tough, and strong, fairly easy to work by cutting, punching, riveting, and welding. Table 4.16 summarizes the most important carbon steels and low-alloy steels used in construction as specified by ASTM.

The plain iron-carbon metals with less than 0.8% carbon content consist of ferrite and pearlite and provide the low-carbon (0.06 to 0.30%), medium-carbon (0.30 to 0.50%), and high-carbon (0.50 to 0.80%) steels called hypoeutectoid steels. The higher-carbon or hypereutectoid tool steels contain 0.8 to 2.0% carbon and consist of pearlite and cementite. The eutectoid steels occurring in the vicinity of 0.8% carbon are essentially all pearlite.

The American Iron and Steel Institute and the Society of Automotive Engineers have designated standard compositions for various steels including plain carbon steels and alloy steels. AISI and SAE numbers and compositions for several representative hot-rolled carbon-steel bars are given in Table 4.17.

Prestressed concrete imposes special requirements for reinforcing steel. It must be of high strength with a high yield point and minimum creep in the working range. Table 4.16 and 4.18 give ASTM specification requirements for bars, wires, and strands.

4.40.4 Types of Structural Steels

Structural steels are low- to medium-carbon steels used in elements ¼ in thick or more to form structural framing. The American Institute of Steel Construction (AISC) ‘‘Code of Standard Practice for Steel Buildings and Bridges’’ lists the elements that are included in the scope of the work in contract documents for structural steel. The list includes flexural members, columns, trusses, bearings and bearing plates, bracing, hangers, bolts and nuts, shear connectors, wedges, and shims. The AISC ‘‘Specification for Structural Steel Buildings’’ (ASD and LRFD) tabulates the types of structural steel that are approved for use in buildings. These steels are given in Table 4.16.

TABLE 4.17 Standard Steels for Hot-Rolled Bars (Basic open-hearth and acid bessemer carbon steels)

SAE and AISI No.	Chemical composition limits, %			
	Carbon	Manganese	Max phosphorus	Max sulfur
1008	0.10 max	0.30/0.50	0.040	0.050
1010	0.08/0.13	0.30/0.60	0.040	0.050
1015	0.13/0.18	0.30/0.60	0.040	0.050
1020	0.18/0.23	0.30/0.60	0.040	0.050
1025	0.22/0.28	0.30/0.60	0.040	0.050
1030	0.28/0.34	0.60/0.90	0.040	0.050
1040	0.37/0.44	0.60/0.90	0.040	0.050
1050	0.48/0.55	0.60/0.90	0.040	0.050
1070	0.65/0.75	0.60/0.90	0.040	0.050
1084	0.80/0.93	0.60/0.90	0.040	0.050
1095	0.90/1.03	0.30/0.50	0.040	0.050

TABLE 4.18 ASTM Requirements for Prestressing Bars and Wires

Material	ASTM designation	Tensile strength, ksi	Minimum yield strength
Seven-wire steel strand	A416		
Grade 250		250	85% of breaking strength,
Grade 270		170	at 1% extension
Uncoated steel wire	A421		
Type BA		235–240	85% of breaking strength,
Type WA		235–250	at 1% extension
High-strength bar	A722		
Type I		150	85% of tensile strength
Type II		150	80% of tensile strength

In accordance with present practice, the steels described in this section and in Sec. 7 are given the names of the corresponding ASTM specifications for the steels. For example, all steels conforming with ASTM A588, ‘‘Specification for High-Strength Low-Alloy Structural Steel,’’ are called A588 steel. Further identification may be given by a grade, which usually indicates the steel yield strength.

Structural steels may be classified as carbon steels; high-strength, low-alloy steels; heat-treated, high-strength carbon steels; or heat-treated, constructional alloy steels.

Carbon steels satisfy all of the following requirements:

1. The maximum content specified for alloying elements does not exceed the following: manganese, 1.65%; silicon, 0.60%; copper, 0.60%.
2. The specified minimum for copper does not exceed 0.40%.
3. No minimum content is specified for other elements added to obtain a desired alloying effect.

A36 and A529 steels are included in this category.

High-strength, low-alloy steels have specified minimum yield strengths larger than 40 ksi, which are attained without heat treatment. A242, A572, and A588 steels are included in this category. A242 and A572 steel are often referred to as weathering steels, because they have higher resistance to corrosion than carbon steels. On exposure to ordinary atmospheric conditions, they develop a protective oxide surface.

Heat-treated, high-strength carbon steels are heat-treated to achieve specified high strength and toughness. A633, A678, and A852 steels are included in this category.

Heat-treated, constructional alloy steels contain alloying elements in excess of the limits for carbon steels and are heat-treated to obtain a combination of high strength and toughness. These are the strongest steels in general structural use. The various grades of A514 steel, with yield strengths up to 100 ksi, are in this category.

4.41 PROPERTIES OF STRUCTURAL STEELS

Figure 4.3 shows a typical stress-strain curve for each classification of structural steels defined in Art. 4.40.4. The diagram illustrates the higher-strength levels achieved with heat treatment and addition of alloys.

4.41.1 Tensile Properties of Structural Steels

The curves in Fig. 4.3 were derived from tensile tests. The yield points, strengths, and modulus of elasticity obtained from compression tests would be about the same.

The initial portion of the curves in Fig. 4.3 is shown to a magnified scale in Fig. 4.4. It indicates that there is an initial elastic range for the structural steels in which there is no permanent deformation on removal of the load. The modulus of

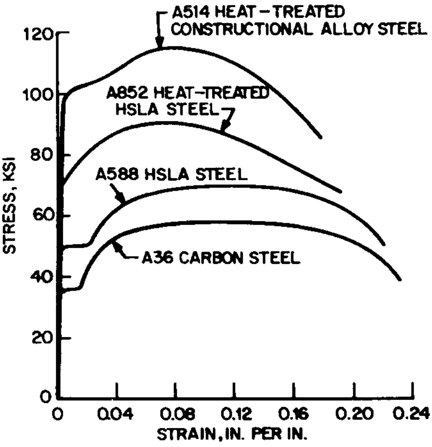

FIGURE 4.3 Typical stress-strain curves for structural steels.

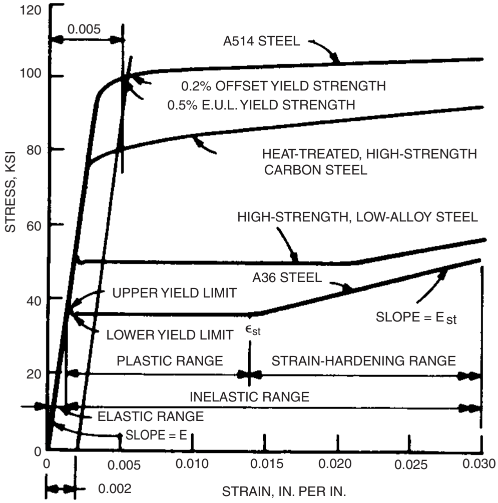

FIGURE 4.4 Magnification of the initial portions of the stress-strain curves for structural steels.

elasticity *E*, which is given by the slope of the curves, is nearly a constant 29,000 ksi for all the steels. For carbon and high-strength, low-alloy steels, the inelastic range, where strains exceed those in the elastic range, consists of two parts: Initially, a plastic range occurs in which the steels yield; that is, strain increases with no increase in stress. Then follows a strain-hardening range in which increase in strain is accompanied by a significant increase in stress.

The curves in Fig. 4.4 also show an upper and lower yield point for the carbon and high-strength, low-alloy steels. The upper yield point is the one specified in standard specifications for the steels. In contrast, the curves do not indicate a yield point for the heat-treated steels. For these steels, ASTM 370, ‘‘Mechanical Testing of Steel Products,’’ recognizes two ways of indicating the stress at which there is a significant deviation from the proportionality of stress to strain. One way, applicable to steels with a specified yield point of 80 ksi or less, is to define the yield point as the stress at which a test specimen reaches a 0.5% extension under load (0.5% *EUL*). The second way is to define the yield strength as the stress at which a test specimen reaches a strain (offset) 0.2% greater than that for elastic behavior. Yield point and yield strength are often referred to as yield stress.

Ductility is measured in tension tests by percent elongation over a given gage length—usually 2 or 8 in—or percent reduction of cross-sectional area. Ductility is an important property because it permits redistribution of stresses in continuous members and at points of high local stresses.

Poisson’s ratio, the ratio of transverse to axial strain, also is measured in tension tests. It may be taken as 0.30 in the elastic range and 0.50 in the plastic range for structural steels.

Cold working of structural steels, that is, forming plates or structural shapes into other shapes at room temperature, changes several properties of the steels. The resulting strains are in the strain-hardening range. Yield strength increases but ductility decreases. (Some steels are cold rolled to obtain higher strengths.) If a steel element is strained into the strain-hardening range, then unloaded and allowed to age at room or moderately elevated temperatures (a process called **strain aging**), yield and tensile strengths are increased, whereas ductility is decreased. Heat treatment can be used to modify the effects of cold working and strain aging.

Residual stresses remain in structural elements after they are rolled or fabricated. They also result from uneven cooling after rolling. In a welded member, tensile residual stresses develop near the weld and compressive stresses elsewhere. Plates with rolled edges have compressive residual stresses at the edges, whereas flame-cut edges have tensile residual stresses. When loads are applied to such members, some yielding may take place where the residual stresses occur. Because of the ductility of steel, however, the effect on tensile strength is not significant but the buckling strength of columns may be lowered.

Strain rate also changes the tensile properties of structural steels. In the ordinary tensile test, load is applied slowly. The resulting data are appropriate for design of structures for static loads. For design for rapid application of loads, such as impact loads, data from rapid tension tests are needed. Such tests indicate that yield and tensile strengths increase but ductility and the ratio of tensile strength to yield strength decrease.

High temperatures too affect properties of structural steels. As temperatures increase, the stress-strain curve typically becomes more rounded and tensile and yield strengths, under the action of strain aging, decrease. Poisson's ratio is not significantly affected but the modulus of elasticity decreases. Ductility is lowered until a minimum value is reached. Then, it rises with increase in temperature and becomes larger than the ductility at room temperature.

Low temperatures in combination with tensile stress and especially with geometric discontinuities, such as notches, bolt holes, and welds, may cause a brittle failure. This is a failure that occurs by cleavage, with little indication of plastic deformation. A ductile failure, in contrast, occurs mainly by shear, usually preceded by large plastic deformation. One of the most commonly used tests for rating steels on their resistance to brittle fracture is the Charpy V-notch test. It evaluates notch toughness at specific temperatures.

Toughness is defined as the capacity of a steel to absorb energy; the greater the capacity, the greater the toughness. Determined by the area under the stress-strain curve, toughness depends on both strength and ductility of the metal. Notch toughness is the toughness in the region of notches or other stress concentrations. A quantitative measure of notch toughness is fracture toughness, which is determined by fracture mechanics from relationships between stress and flaw size.

4.41.2 Shear Properties of Structural Steels

The shear modulus of elasticity G is the ratio of shear stress to shear strain during initial elastic behavior. It can be computed from Eq. (5.25) from values of modulus of elasticity and Poisson's ratio developed in tension stress-strain tests. Thus G for structural steels is generally taken as 11,000 ksi.

The shear strength, or shear stress at failure in pure shear, ranges from $0.67F_t$ to $0.75F_t$ for structural steels, where F_t is the tensile strength. The yield strength in shear is about $0.57F_t$.

4.41.3 Creep and Relaxation

Creep, a gradual change in strain under constant stress, is usually not significant for structural steel framing in buildings, except in fires. Creep usually occurs under high temperatures or relatively high stresses, or both.

Relaxation, a gradual decrease in load or stress under a constant strain, is a significant concern in the application of steel tendons to prestressing (Art. 9.104). With steel wire or strand, relaxation can occur at room temperature. To reduce relaxation substantially, stabilized, or low-relaxation, strand may be used. This is produced by pretensioning strain at a temperature of about 600°F. A permanent elongation of about 1% remains and yield strength increases to about 5% over stress-relieved (heat-treated but not tensioned) strain.

4.41.4 Hardness of Structural Steels

Hardness is used in production of steels to estimate tensile strength and to check the uniformity of tensile strength in various products. Hardness is determined as a number related to resistance to indentation. Any of several tests may be used, the resulting hardness numbers being dependent on the type of penetrator and load. These should be indicated when a hardness number is given. Commonly used hardness tests are the Brinell, Rockwell, Knoop, and Vickers. ASTM A370, ‘‘Mechanical Testing of Steel Products,’’ contains tables that relate hardness numbers from the different tests to each other and to the corresponding approximate tensile strength.

4.41.5 Fatigue of Structural Steels

Under cyclic loading, especially when stress reversal occurs, a structural member may eventually fail because cracks form and propagate. Known as a fatigue failure, this can take place at stress levels well below the yield stress. Fatigue resistance may be determined by a rotating-beam test, flexure test, or axial-load test. In these tests, specimens are subjected to stresses that vary, usually in a constant stress range between maximum and minimum stresses until failure occurs. Results of the tests are plotted on an *S-N* diagram, where *S* is the maximum stress (fatigue strength) and *N* is the number of cycles to failure (fatigue life). Such diagrams indicate that the failure strength of a structural steel decreases with increase in the number of cycles until a minimum value is reached, the **fatigue limit.** Presumably, if the maximum stress does not exceed the fatigue limit, an unlimited number of cycles of that ratio of maximum to minimum stress can be applied without failure. With tension considered positive and compression, negative, tests also show that as the ratio of maximum to minimum stress is increased, fatigue strength is lowered significantly.

Since the tests are made on polished specimens and steel received from mills has a rough surface, fatigue data for design should be obtained from tests made on as-received material.

Tests further indicate that steels with about the same tensile strength have about the same fatigue strength. Hence the *S-N* diagram obtained for one steel may be used for other steels with about the same tensile strength.

4.42 HEAT TREATMENT AND HARDENING OF STEELS

Heat-treated and hardened steels are sometimes required in building operations. The most familiar heat treatment is annealing, a reheating operation in which the metal is usually heated to the austenitic range (Fig. 4.2) and cooled slowly to obtain the softest, most ductile state. Cold working is often preceded by annealing. Annealing may be only partial, just sufficient to relieve internal stresses that might cause deformation or cracking, but not enough to reduce markedly the increased strength and yield point brought about by the cold working, for example.

Another type of heat treatment that may be used is normalizing. It requires heating steel to 100 to 150°F above the A_3 temperature line in Fig. 4.2. Then, the steel is allowed to cool in still air. (The rate of cooling is much more rapid than that used in annealing.) Normalizing may be used to refine steel grain size, which depends on the finishing temperature during hot rolling, or to obtain greater notch toughness.

Thick plates have a coarser grain structure than thin plates and thus can benefit more from normalizing. This grain structure results from the fewer rolling passes required for production of thick plates, consequent higher finishing temperature, and slower cooling.

Sometimes, a hard surface is required on a soft, tough core. Two principal case-hardening methods are employed. For **case carburizing,** a low- to medium-carbon steel is packed in carbonaceous materials and heated to the austenite range. Carbon diffuses into the surface, providing a hard, high-carbon case when the part is cooled. For **nitriding,** the part is exposed to ammonia gas or a cyanide at moderately elevated temperatures. Extremely hard nitrides are formed in the case and provide a hard surface.

4.43 EFFECTS OF GRAIN SIZE

When a low-carbon steel is heated above the A_3 temperature line (Fig. 4.2), for example, to hot rolling and forging temperatures, the steel may grow coarse grains. For some applications, this structure may be desirable; for example, it permits relatively deep hardening, and if the steel is to be used in elevated-temperature service, it will have higher load-carrying capacity and higher creep strength than if the steel had fine grains.

Fine grains, however, enhance many steel properties: notch toughness, bendability, and ductility. In quenched and tempered steels, higher yield strengths are obtained. Furthermore, fine-grain, heat-treated steels have less distortion, less quench cracking, and smaller internal stresses.

During the production of a steel, grain growth may be inhibited by an appropriate dispersion of nonmetallic inclusions or by carbides that dissolve slowly or remain undissolved during cooling. The usual method of making fine-grain steel employs aluminum deoxidation. In such steels, the inhibiting agent may be a submicroscopic dispersion of aluminum nitride or aluminum oxide. Fine grains also may be produced by hot working rolled or forged products, which otherwise would have a coarse-grain structure. The temperature at the final stage of hot working determines the final grain size. If the finishing temperature is relatively high and the grains after air-cooling are coarse, the size may be reduced by normalizing (Art. 4.42). Fine- or coarse-grain steels may be heat treated to be coarse- or fine-grain.

4.44 STEEL ALLOYS

Plain carbon steels can be given a great range of properties by heat treatment and by working; but addition of alloying elements greatly extends those properties or makes the heat-treating operations easier and simpler. For example, combined high tensile strength and toughness, corrosion resistance, high-speed cutting, and many other specialized purposes require alloy steels. However, the most important effect of alloying is the influence on hardenability.

4.44.1 Effects of Alloying Elements

Important alloying elements from the standpoint of building, and their principal effects, are summarized below:

Aluminum restricts grain growth during heat treatment and promotes surface hardening by nitriding.

Chromium is a hardener, promotes corrosion resistance (see Art. 4.44.2), and promotes wear resistance.

Copper promotes resistance to atmospheric corrosion and is sometimes combined with molybdenum for this purpose in low-carbon steels and irons. It strengthens steel and increases the yield point without unduly changing elongation or reduction of area.

Manganese in low concentrations promotes hardenability and nondeforming, nonshrinking characteristics for tool steels. In high concentrations, the steel is austenitic under ordinary conditions, is extremely tough, and work-hardens readily. It is therefore used for teeth of power-shovel dippers, railroad frogs, rock crushers, and similar applications.

Molybdenum is usually associated with other elements, especially chromium and nickel. It increases corrosion resistance, raises tensile strength and elastic limit without reducing ductility, promotes casehardening, and improves impact resistance.

Nickel boosts tensile strength and yield point without reducing ductility; increases low-temperature toughness, whereas ordinary carbon steels become brittle; promotes casehardening; and in high concentrations improves corrosion resistance under severe conditions. It is often used with chromium (see Art. 4.44.2). **Invar** contains 36% nickel.

Silicon strengthens low-alloy steels; improves oxidation resistance; with low carbon yields transformer steel, because of low hysteresis loss and high permeability; in high concentrations provides hard, brittle castings, resistant to corrosive chemicals, useful in plumbing lines for chemical laboratories.

Sulfur promotes free machining, especially in mild steels.

Titanium prevents intergranular corrosion of stainless steels by preventing grain-boundary depletion of chromium during such operations as welding and heat treatment.

Tungsten, vanadium, and **cobalt** are all used in high-speed tool steels, because they promote hardness and abrasion resistance. Tungsten and cobalt also increase high-temperature hardness.

The principal effects of alloying elements are summarized in Table 4.19.

4.44.2 Stainless Steels

Stainless steels of primary interest in building are the wrought stainless steels of the austenitic type. The austenitic stainless steels contain both chromium and nickel. Total content of alloy metals is not less than 23%, with chromium not less than 16% and nickel not less than 7%. Commonly used stainless steels have a tensile

TABLE 4.19 Effects of Alloying Elements in Steel*

Element	Solid solubility		Influence on ferrite	Influence on austenite (hardenability)	Influence exerted through carbide		Principal functions
	In gamma iron	In alpha iron			Carbide-forming tendency	Action during tempering	
Aluminum (Al)	1.1% (increased by C)	36%	Hardens considerably by solid solution	Increases hardenability mildly, if dissolved in austenite	Negative (graphitizes)		1. Deoxides efficiently 2. Restricts grain growth (by forming dispersed oxides or nitrides) 3. Alloying element in nitriding steel
Chromium (Cr)	12.8% (20% with 0.5% C)	Unlimited	Hardens slightly; increases corrosion resistance	Increases hardenability moderately	Greater than Mn; less than W	Mildly resists softening	1. Increases resistance to corrosion and oxidation 2. Increases hardenability 3. Adds some strength at high temperatures 4. Resists abrasion and wear (with high carbon)
Cobalt (Co)	Unlimited	75%	Hardens considerably by solid solution	Decreases hardenability as dissolved	Similar to Fe	Sustains hardness by solid solution	1. Contribute to red hardness by hardening ferrite

TABLE 4.19 Effects of Alloying Elements in Steel* (*Continued*)

Element	Solid solubility		Influence on ferrite	Influence on austenite (hardenability)	Influence exerted through carbide		Principal functions
	In gamma iron	In alpha iron			Carbide-forming tendency	Action during tempering	
Manganese (Mn)	Unlimited	3%	Hardens markedly; reduces plasticity somewhat	Increases hardenability moderately	Greater than Fe; less than Cr	Very little, in usual percentages	1. Counteracts brittleness from the sulfur 2. Increases hardenability inexpensively
Molybdenum (Mo)	3% ± (8% with 0.3% C)	37.5% (less with lowered temp)	Provides age-hardening system in high Mo-Fe alloys	Increases hardenability strongly (Mo $>$ Cr)	Strong; greater than Cr	Opposes softening by secondary hardening	1. Raises grain-coarsening temperature of austenite 2. Deepens hardening 3. Counteracts tendency toward temper brittleness 4. Raises hot and creep strength, red hardness 5. Enhances corrosion resistance in stainless steel 6. Forms abrasion-resisting particles
Nickel (Ni)	Unlimited	10% (irrespective of carbon content)	Strengthens and toughens by solid solution	Increases hardenability mildly, but tends to retain austenite with higher carbon	Negative (graphitizes)	Very little in small percentages	1. Strengthens unquenched or annealed steels 2. Toughness pearlitic-ferric steels (especially at low temperatures) 3. Renders high-chromium iron alloys austenitic

TABLE 4.19 Effects of Alloying Elements in Steel* (*Continued*)

Element	Solid solubility		Influence on ferrite	Influence on austenite (hardenability)	Influence exerted through carbide		Principal functions
	In gamma iron	In alpha iron			Carbide-forming tendency	Action during tempering	
Phosphorus (P)	0.5%	2.8% (irrespective of carbon content)	Hardens strongly by solid solution	Increases hardenability	Nil		1. Strengthens low-carbon steel 2. Increases resistance to corrosion 3. Improves machinability in free-cutting steels
Silicon (Si)	2% ± (9% with 0.35% C)	18.5% (not much changed by carbon)	Hardens with loss in plasticity ($Mn < Si < P$)	Increases hardenability moderately	Negative (graphitizes)	Sustains hardness by solid solution	1. Used as general-purpose deoxidizer 2. Alloying element for electrical and magnetic sheet 3. Improves oxidation resistance 4. Increases hardenability of steel carrying nongraphitizing elements 5. Strengthens low-alloy steels

Titanium (Ti)	0.75% (1% ± with 0.20% C)	6% ± (less with lowered temp)	Provides age-hardening system in high Ti-Fe alloys	Probably increases hardenability very strongly as dissolved. The carbide effects reduce hardenability	Greatest known (2% Ti renders 0.50% carbon steel unhardenable)	Persistent carbides probably unaffected. Some secondary hardening	1. Fixes carbon in inert particles a. Reduces martensitic hardness and hardenability in medium-chromium steels b. Prevents formation of austenite in high-chromium steels c. Prevents localized depletion of chromium in stainless steel during long heating.
Tungsten (W)	6% (11% with 0.25% C)	33% (less with lowered temp)	Provides age-hardening system in high W-Fe alloys	Increases hardenability strongly in small amounts	Strong	Opposes softening by secondary hardening	1. Forms hard, abrasion-resistant particles in tool steels 2. Promotes hardness and strength at elevated temperature
Vanadium (V)	1% (4% with 0.20% C)	Unlimited	Hardens moderately by solid solution	Increases hardenability very strongly, as dissolved	Very strong (V < Ti or Cb)	Max for secondary hardening	1. Elevates coarsening temperature of austenite (promotes fine grain) 2. Increases hardenability (when dissolved) 3. Resists tempering and causes marked secondary hardening

* "Metals Handbook," American Society for Metals.

strength of 75 ksi and yield point of 30 ksi when annealed. Cold-finished steels may have a tensile strength as high as 125 ksi with a yield point of 100 ksi.

Austenitic stainless steels are tough, strong, and shock-resistant, but work-harden readily; so some difficulty on this score may be experienced with cold working and machining. These steels can be welded readily but may have to be stabilized (e.g., AISI Types 321 and 347) against carbide precipitation and intergranular corrosion due to welding unless special precautions are taken. These steels have the best high-temperature strength and resistance to scaling of all the stainless steels.

Types 303 and 304 are the familiar 18-8 stainless steels widely used for building applications. These and Types 302 and 316 are the most commonly employed stainless steels. Where maximum resistance to corrosion is required, such as resistance to pitting by seawater and chemicals, the molybdenum-containing Types 316 and 317 are best.

For resistance to ordinary atmospheric corrosion, some of the martensitic and ferritic stainless steels, containing 15 to 20% chromium and no nickel, are employed. The martensitic steels, in general, range from about 12 to 18% chromium and from 0.08 to 1.10% carbon. Their response to heat treatment is similar to that of the plain carbon steels. When chromium content ranges from 15 to 30% and carbon content is below 0.35%, the steels are ferritic and nonhardenable. The high-chromium steels are resistant to oxidizing corrosion and are useful in chemical plants.

4.45 WELDING FERROUS METALS

General welding characteristics of the various types of ferrous metals are as follows:

Wrought iron is ideally forged but may be welded by other methods if the base metal is thoroughly fused. Slag melts first and may confuse unwary operators.

Low-carbon iron and steels (0.30%C or less) are readily welded and require no preheating or subsequent annealing unless residual stresses are to be removed.

Medium-carbon steels (0.30 to 0.50%C) can be welded by the various fusion processes. In some cases, especially in steel with more than 0.40% carbon, preheating and subsequent heat treatment may be necessary.

High-carbon steels (0.50 to 0.90%C) are more difficult to weld and, especially in arc welding, may have to be preheated to at least 500°F and subsequently heated between 1200 and 1450°F. For gas welding, a carburizing flame is often used. Care must be taken not to destroy the heat treatment to which high-carbon steels may have been subjected.

Tool steels (0.80 to 1.50%C) are difficult to weld. Preheating, postannealing, heat treatment, special welding rods, and great care are necessary for successful welding.

Welding of structural steels is governed by the American Welding Society ‘‘Structural Welding Code,’’ AWS D1.1, the American Institute of Steel Construction Specification for the Design, Fabrication and Erection of Structural Steel for Buildings, or a local building code. AWS D1.1 specifies tests to be used in qualifying welders and types of welds. The AISC Specification and many building codes require, in general, that only qualified welds be used and that they be made only by qualified welders.

Structural steels may be welded by shielded metal arc, submerged arc, gas metal arc, flux-cored arc, electroslag, electrogas, or stud-welding processes.

Shielded-metal-arc welding fuses parts to be joined by the heat of an electric arc struck between a coated metal electrode and the material being joined, or base metal. The electrode supplies filler material for making the weld, gas for shielding the molten metal from the air, and flux for refining this metal.

Submerged-arc welding fuses the parts to be joined by the heat of an electric arc struck between a bare metal electrode and base metal. The weld is shielded from the air by flux. The electrode or a supplementary welding rod supplies metal filler for making the weld.

Gas-metal-arc welding produces fusion by the heat of an electric arc struck between a filler-metal electrode and base metal, while the molten metal is shielded by a gas or mixture of gas and flux. For structural steels, the gas may be argon, argon with oxygen, or carbon dioxide.

Electroslag welding uses a molten slag to melt filler metal and surfaces of the base metal and thus make a weld. The slag, electrically conductive, is maintained molten by its resistance to an electric current that flows between an electrode and the base metal. The process is suitable only for welding in the vertical position. Moving, water-cooled shoes are used to contain and shape the weld surface. The slag shields the molten metal.

Electrogas welding is similar to the electroslag process. The electrogas process, however, maintains an electric arc continuously, uses an inert gas for shielding, and the electrode provides flux.

Stud welding is used to fuse metal studs or similar parts to other steel parts by the heat of an electric arc. A welding gun is usually used to establish and control the arc, and to apply pressure to the parts to be joined. At the end to be welded, the stud is equipped with a ceramic ferrule, which contains flux and which also partly shields the weld when molten.

Preheating before welding reduces the risk of brittle failure. Initially, its main effect is to lower the temperature gradient between the weld and adjoining base metal. This makes cracking during cooling less likely and gives entrapped hydrogen, a possible source of embrittlement, a chance to escape. A later effect of preheating is improved ductility and notch toughness of base and weld metals and lower transition temperature of weld. When, however, welding processes that deposit weld metal low in hydrogen are used and suitable moisture control is maintained, the need for preheat can be eliminated. Such processes include use of low-hydrogen electrodes and inert-arc and submerged-arc welding.

Rapid cooling of a weld can have an adverse effect. One reason that arc strikes that do not deposit weld metal are dangerous is that the heated metal cools very fast. This causes severe embrittlement. Such arc strikes should be completely removed. The material should be preheated, to prevent local hardening, and weld metal should be deposited to fill the depression.

Pronounced segregation in base metal may cause welds to crack under certain fabricating conditions. These include use of high-heat-input electrodes, such as the ¼-in E6020, and deposition of large beads at slow speeds, as in automatic welding. Cracking due to segregation, however, is rare with the degree of segregation normally occurring in hot-rolled carbon-steel plates.

Welds sometimes are peened to prevent cracking or distortion, though there are better ways of achieving these objectives. Specifications often prohibit peening of the first and last weld passes. Peening of the first pass may crack or punch through the weld. Peening of the last pass makes inspection for cracks difficult. But peening is undesirable because it considerably reduces toughness and impact properties of the weld metal. (The adverse effects, however, are eliminated by a covering weld layer.) The effectiveness of peening in preventing cracking is open to question. And for preventing distortion, special welding sequences and procedures are simpler and easier.

Failures in service rarely, if ever, occur in properly made welds of adequate design. If a fracture occurs, it is initiated at a notchlike defect. Notches occur for various reasons. The toe of a weld may from a natural notch. The weld may contain flaws that act as notches. A welding-arc strike in the base metal may have an embrittling effect, especially if weld metal is not deposited. A crack started at such notches will propagate along a path determined by local stresses and notch toughness of adjacent material.

Weldability of structural steels is influenced by their chemical content. Carbon, manganese, silicon, nickel, chromium, and copper, for example, tend to have an adverse effect, whereas molybdenum and vanadium may be beneficial. To relate the influence of chemical content on structural steel properties to weldability, the use of a carbon equivalent has been proposed. One formula suggested is

$$C_{eq} = C + \frac{Mn}{4} + \frac{Si}{4} \tag{4.3}$$

where C = carbon content, %
Mn = manganese content, %
Si = silicon content, %

Another proposed formula includes more elements:

$$C_{eq} = C + \frac{Mn}{6} + \frac{Ni}{20} + \frac{Cr}{10} - \frac{Mo}{50} - \frac{V}{10} + \frac{Cu}{40} \tag{4.4}$$

where Ni = nickel content, %
Cr = chromium content, %
Mo = molybdenum content, %
V = vanadium content, %
Cu = copper content, %

Carbon equivalent appears to be related to the maximum rate at which a weld and adjacent base metal may be cooled after welding without underbead cracking occurring. The higher the carbon equivalent, the lower will be the allowable cooling rate. Also, the higher the carbon equivalent, the more important use of low-hydrogen electrodes and preheating becomes.

4.46 EFFECTS OF STEEL PRODUCTION METHODS

The processing of steels after conversion of pig iron to steel in a furnace has an important influence on the characteristics of the final products. The general procedure is as follows: The molten steel at about 2900°F is fed into a steel ladle, a refractory-lined open-top vessel. Alloying materials and deoxidizers may be added during the tapping of the heat or to the ladle. From the ladle, the liquid steel is poured into molds, where it solidifies. These castings, called ingots, then are placed in special furnaces, called soaking pits. There, the ingots are held at the desired temperature for rolling until the temperature is uniform throughout each casting.

Ideally, an ingot should be homogeneous, with a fine, equiaxial crystal structure. It should not contain nonmetallic inclusions or cavities and should be free of chemical segregation. In practice, however, because of uneven cooling and release of gases in the mold, an ingot may develop any of a number of internal and external defects. Some of these may be eliminated or minimized during the rolling operation. Prevention or elimination of the others often adds to the cost of steels.

Steel cools unevenly in a mold, because the liquid at the mold walls solidifies first and cools more rapidly than metal in the interior of the ingot. Gases, chiefly oxygen, dissolved in the liquid, are released as the liquid cools. Four types of ingot may result—killed, semikilled, capped, and rimmed—depending on the amount of gases dissolved in the liquid, the carbon content of the steel, and the amount of deoxidizers added to the steel.

A fully killed ingot develops no gas; the molten steel lies dead in the mold. The top surface solidifies relatively fast. Pipe, an intermittently bridged shrinkage cavity, forms below the top. Fully killed steels usually are poured in big-end-up molds with ‘‘hot tops’’ to confine the pipe to the hot top, which is later discarded. A semikilled ingot develops a slight amount of gas. The gas, trapped when the metal solidifies, forms blowholes in the upper portion of the ingot. A **capped ingot** develops rimming action, a boiling caused by evolution of gas, forcing the steel to rise. The action is stopped by a metal cap secured to the mold. Strong upward currents along the sides of the mold sweep away bubbles that otherwise would form blowholes in the upper portion of the ingot. Blowholes do form, however, in the lower portion, separated by a thick solid skin from the mold walls. A **rimmed ingot** develops a violent rimming action, confining blowholes to only the bottom quarter of the ingot.

Rimmed or capped steels cannot be produced if too much carbon is present (0.30% or more), because insufficient oxygen will be dissolved in the steels to cause the rimming action. Killed and semikilled steels require additional costs for deoxidizers if carbon content is low, and the deoxidation products form nonmetallic inclusions in the ingot. Hence, it often is advantageous for steel producers to make low-carbon steels by rimmed or capped practice, and high-carbon steels by killed or semikilled practice.

Pipe, or shrinkage cavities, generally is small enough in most steels to be eliminated by rolling. **Blowholes** in the interior of an ingot, small voids formed by entrapped gases, also usually are eliminated during rolling. If they extend to the surface, they may be oxidized and form seams when the ingot is rolled, because the oxidized metal cannot be welded together. Properly made ingots have a thick enough skin over blowholes to prevent oxidation.

Segregation in ingots depends on the chemical composition and on turbulence from gas evolution and convection currents in the molten metal. Killed steels have less segregation than semikilled steels, and these types of steels have less segregation than capped or rimmed steels. In rimmed steels, the effects of segregation are so marked that interior and outer regions differ enough in chemical composition to appear to be different steels. The boundary between these regions is sharp.

Rimmed steels are made without additions of deoxidizers to the furnace and with only small additions to the ladle, to ensure sufficient evolution of gas. When properly made, rimmed ingots have little pipe and a good surface. Such steels are preferred where surface finish is important and the effects of segregation will not be harmful.

Capped steels are made much like rimmed steels but with less rimming action. Capped steels have less segregation. They are used to make sheet, strip, skelp, tinplate, wire, and bars.

Semikilled steel is deoxidized less than killed steel. Most deoxidation is accomplished with additions of a deoxidizer to the ladle. Semikilled steels are used in structural shapes and plates.

Killed steels usually are deoxidized by additions to both furnace and ladle. Generally, silicon compounds are added to the furnace to lower the oxygen content of the liquid metal and stop oxidation of carbon (block the heat). This also permits addition of alloying elements that are susceptible to oxidation. Silicon or other deoxidizers, such as aluminum, vanadium, and titanium, may be added to the ladle to complete deoxidation. Aluminum, vanadium, and titanium have the additional beneficial effect of inhibiting grain growth when the steel is normalized. (In the hot-rolled conditions, such steels have about the same ferrite grain size as semikilled steels.) Killed steels deoxidized with aluminum and silicon (made to fine-grain practice) often are specified for construction applications because of better notch toughness and lower transition temperatures than semikilled steels of the same composition.

4.47 EFFECTS OF HOT ROLLING

While plates and shapes for construction applications can be obtained from processes other than casting and rolling of ingots, such as continuous casting, most plates and shapes are made by hot-rolling ingots (Art. 4.46). But usually, the final products are not rolled directly from ingots. First, the ingots are generally reduced in cross section by rolling into billets, slabs, and blooms. These forms permit correction of defects before finish rolling, shearing into convenient lengths for final rolling, reheating for further rolling, and transfer to other mills, if desired, for that processing.

Plates produced from slabs or directly from ingots, are distinguished from sheet, strip, and flat bars by size limitations in ASTM A6. Generally, plates are heavier, per linear foot, than these other products. Sheared plates, or sheared mill plates, are made with straight horizontal rolls and later trimmed on all edges. Universal plates, or universal mill plates, are formed between vertical and horizontal rolls and are trimmed on the ends only.

Some of the plates may be heat-treated, depending on grade of steel and intended use. For carbon steel, the treatment may be annealing, normalizing, or stress relieving. Plates of high-strength, low-alloy constructional steels may be quenched and tempered. See Art. 4.42.

Shapes are rolled from blooms that first are reheated to 2250°F. Rolls gradually reduce the plastic blooms to the desired shapes and sizes. The shapes then are cut to length for convenient handling with a hot saw.

ASTM A6 requires that material for delivery ‘‘shall be free from injurious defects and shall have a workmanlike finish.’’ The specification permits manufacturers to condition plates and shapes ‘‘for the removal of injurious surface imperfections or surface depressions by grinding, or chipping and grinding. . . .’’

Internal structure and many properties of plates and shapes are determined largely by the chemistry of the steel, rolling practice, cooling conditions after rolling, and heat treatment, where used. The interior of ingots consists of large crystals, called dendrites, characterized by a branching structure. Growth of individual dendrites occurs principally along their longitudinal axes perpendicular to the ingot surfaces. Heating for rolling tends to eliminate dendritic segregation, so that the rolled products are more homogeneous than ingots. Furthermore, during rolling, the dendritic structure is broken up. Also, recrystallization occurs. The final austenitic grain size is determined by the temperature of the steel during the last passes through the rolls (Art. 4.43). In addition, dendrites and inclusions are reoriented in the direction of rolling. As a result, ductility and bendability are much better in the longitudinal direction than in the transverse, and these properties are poorest in the thickness direction. The cooling rate after rolling determines the distribution of ferrite and the grain size of the ferrite.

In addition to the preceding effects, rolling also may induce residual stresses in plates and shapes (Art. 4.41.1). Still other effects are a consequence of the final thickness of the hot-rolled material.

Thicker material requires less rolling, the finish rolling temperature is higher, and the cooling rate is slower than for thin material. As a consequence, thin material has a superior microstructure. Furthermore, thicker material can have a more unfavorable state of stress because of stress raisers, such as tiny cracks and inclusions, and residual stresses. Consequently, thin material develops higher tensile and yield strengths than thick material of the same steel. ASTM specifications for structural steels recognize this usually by setting lower yield points for thicker material. A36 steel, however, has the same yield point for all thicknesses. To achieve this, the chemistry is varied for plates and shapes and for thin and thick plates. Thicker plates contain more carbon and manganese to raise the yield point. This cannot be done for high-strength steels because of the adverse effect on notch toughness, ductility, and weldability.

Thin material has greater ductility than thick material of the same steel. Since normalizing refines the grain structure, thick material improves relatively more with normalizing than does thin material. The improvement is even greater with silicon-aluminum-killed steels.

4.48 EFFECTS OF PUNCHING AND SHEARING

Punching holes and shearing during fabrication are cold-working operations that can cause brittle failure. Bolt holes, for example, may be formed by drilling, punching, or punching followed by reaming. Drilling is preferable to punching, because punching drastically cold-works the material at the edge of a hole. This makes the steel less ductile and raises the transition temperature. The degree of embrittlement depends on type of steel and plate thickness. Furthermore, there is a possibility that punching can produce short cracks extending radially from the hole. Consequently, brittle failure can be initiated at the hole when the member is stressed.

Should the material around the hole become heated, an additional risk of failure is introduced. Heat, for example, may be supplied by an adjacent welding operation. If the temperature should rise to the 400 to 850°F range, strain aging will occur in material susceptible to it. The result will be a loss in ductility.

Reaming a hole after punching can eliminate the short radial cracks and the risks of embrittlement. For the purpose, the hole diameter should be increased by $\frac{1}{16}$ to $\frac{1}{4}$ in by reaming, depending on material thickness and hole diameter.

Shearing has about the same effects as punching. If sheared edges are to be left exposed, $\frac{1}{16}$ in or more material, depending on thickness, should be trimmed by gas cutting. Note also that rough machining, for example, with edge planers making a deep cut, can produce the same effects as shearing or punching.

4.49 CORROSION OF IRON AND STEEL

Corrosion of ferrous metals is caused by the tendency of iron (anode) to go into solution in water as ferrous hydroxide and displace hydrogen, which in turn combines with dissolved oxygen to form more water. At the same time, the dissolved ferrous hydroxide is converted by more oxygen to the insoluble ferric hydroxide, thereby allowing more iron to go into solution. Corrosion, therefore, requires liquid water (as in damp air) and oxygen (which is normally present dissolved in the water).

Alloying elements can increase the resistance of steel considerably. For example, addition of copper to structural steels A36 and A529 can about double their corrosion resistance. Other steels, such as A242 and A588, are called weathering steels, because they have three to four times the resistance of A36 steel (Art. 4.40.4).

Protection against corrosion takes a variety of forms:

Deaeration. If oxygen is removed from water, corrosion stops. In hot-water heating systems, therefore, no fresh water should be added. Boiler feedwater is sometimes deaerated to retard corrosion.

Coatings

1. **Paints.** Most paints are based on oxidizing oil and a variety of pigments, of which oxides of iron, zinc sulfate, graphite, aluminum, and various hydrocarbons are a few. No one paint is best for all applications. Other paints are coatings of asphalt and tar. The AISC ‘‘Specification for Structural Steel Buildings’’ (ASD and LRFD) states that, in general, steelwork to be concealed within a building need not be painted and that steel to be encased in concrete should not be painted. Inspections of old buildings have revealed that concealed steelwork withstands corrosion virtually to the same degree whether or not it is painted.
2. **Metallic.** Zinc is applied by hot dipping (**galvanizing**) or powder (**sherardizing),** hot tin drip, hot aluminum dip, and electrolytic plates of tin, copper, nickel, chromium, cadmium, and zinc. A mixture of lead and tin is called **terneplate.** Zinc is anodic to iron and protects, even after the coating is broken, by sacrificial protection. Tin and copper are cathodic and protect as long as the coating is unbroken but may hasten corrosion by pitting and other localized action once the coating is pierced.
3. **Chemical.** Insoluble phosphates, such as iron or zinc phosphate, are formed on the surface of the metal by treatment with phosphate solutions. These have some protective action and also form good bases for paints. Black oxide coatings are formed by treating the surface with various strong salt solutions. These coatings are good for indoor use but have limited life outdoors. They provide a good base for rust-inhibiting oils.

Cathodic Protection. As corrosion proceeds, electric currents are produced as the metal at the anode goes into solution. If a sufficient countercurrent is produced, the metal at the anode will not dissolve. This is accomplished in various ways, such as connecting the iron to a more active metal like magnesium (rods suspended in domestic water heaters) or connecting the part to be protected to buried scrap iron and providing an external current source such as a battery or rectified current from a power line (protection of buried pipe lines).

4.50 STEEL AND STEEL ALLOY BIBLIOGRAPHY

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ALUMINUM AND ALUMINUM-BASED ALLOYS

Pure aluminum and aluminum alloys are used in buildings in various forms. High-purity aluminum (at least 99% pure) is soft and ductile but weak. It has excellent corrosion resistance and is used in buildings for such applications as bright foil for heat insulation, roofing, flashing, gutters and downspouts, exterior and interior architectural trim, and as pigment in aluminum-based paints. Its high heat conductivity recommends it for cooking utensils. The electrical conductivity of the electrical grade is 61% of that of pure copper on an equal-volume basis and 201% on an equal-weight basis.

Aluminum alloys are generally harder and stronger than the pure metal. Furthermore, pure aluminum is difficult to cast satisfactorily, whereas many of the alloys are readily cast.

Pure aluminum is generally more corrosion resistant than its alloys. Furthermore, its various forms—pure and alloy—have different solution potentials; that is, they are anodic or cathodic to each other, depending on their relative solution potentials. A number of alloys are therefore made with centers or ‘‘cores’’ of aluminum alloys, overlaid with layers of metal, either pure aluminum or alloys, which are anodic to the core. If galvanic corrosion conditions are encountered, the cladding metal protects the core sacrifically.

4.51 ALUMINUM-ALLOY DESIGNATIONS

The alloys may be classified: (1) as cast and wrought, and (2) as heat-treatable and non-heat-treatable. Wrought alloys can be worked mechanically by such processes as rolling, extruding, drawing, or forging. Alloys are heat-treatable if the dissolved constituents are less soluble in the solid state at ordinary temperatures than at elevated temperatures, thereby making age-hardening possible. When heat-treated to obtain complete solution, the product may be unstable and tend to age spontaneously. It may also be treated to produce stable tempers of varying degree. Cold working or strain hardening is also possible, and combinations of tempering and strain hardening can also be obtained.

Because of these various possible combinations, a system of letter and number designations has been worked out by the producers of aluminum and aluminum alloys to indicate the compositions and the tempers of the various metals. Wrought alloys are designated by a four-digit index system. 1xxx is for 99.00% aluminum minimum. The last two digits indicate the minimum aluminum percentage. The second digit represents impurity limits. (EC is a special designation for electrical conductors.) 2xxx to 8xxx represent alloy groups in which the first number indicates the principal alloying constituent, and the last two digits are identifying numbers in the group. The second digit indicates modification of the basic alloy. The alloy groups are listed in Table 4.20.

For cast alloys, a similar designation system is used. The first two digits identify the alloy or its purity. The last digit, preceded by a decimal point, indicates the form of the material; for example, casting or ingot. Casting alloys may be sand or permanent-mold alloys.

Among the wrought alloys, the letter F, O, H, W, and T indicate various basic temper designations. These letters in turn may be followed by numerals to indicate various degrees of treatment. Temper designations are summarized in Table 4.21.

The structural alloys general employed in building fall in the 2xxx, 5xxx, and 6xxx categories. Architectural alloys often used include 3xxx, 5xxx, and 6xxx groups.

4.52 FINISHES FOR ALUMINUM

Almost all finishes used on aluminum may be divided into three major categories in the system recommended by the The Aluminum Association: mechanical finishes, chemical finishes, and coatings. The last may be subdivided into anodic coatings, resinous and other organic coatings, vitreous coatings, electroplated and other metallic coatings, and laminated coatings.

In The Aluminum Association system, mechanical and chemical finishes are designated by M and C, respectively, and each of the five classes of coating is also designated by a letter. The various finishes in each category are designated by two-digit numbers after a letter. The principal finishes are summarized in Table 4.22.

4.53 STRUCTURAL ALUMINUM

Structural aluminum shapes are produced by extrusion. Angles, I beams, and channels are available in standard sizes and in lengths up to 85 ft. Plates up to 6 in thick and 200 in wide also may be obtained.

TABLE 4.20 Aluminum Association Designations for Wrought Aluminum Alloys

Copper	2xxx
Manganese	3xxx
Silicon	4xxx
Magnesium	5xxx
Magnesium and silicon	6xxx
Zinc	7xxx
Other elements	8xxx
Unused series	9xxx

TABLE 4.21 Basic Temper Designations for Wrought Aluminum Alloys*

−F	**As fabricated.** This designation applies to the products of shaping processes in which no special control over thermal conditions or strain hardening is employed. For wrought products, there are no mechanical property limits.
−O	**Annealed.** This designation applies to wrought products annealed to obtain the lowest-strength temper, and to cast products annealed to improve ductility and dimensional stability.
−H†	**Strain hardened (wrought products only).** This designation applies to products that have their strength increased by strain hardening, with or without supplementary thermal treatments to produce some reduction in strengths. The H is always followed by two or more digits.
−W	**Solution heat treated.** An unstable temper applicable only to alloys that spontaneously age at room temperature after solution heat treatment. This designation is specific only when the period of natural aging is indicated: for example W ½ hr.
−T‡	**Thermally treated to produce stable tempers other than F, O, or H.** This designation applies to products that are thermally treated, with or without supplementary strain hardening, to produce stable tempers. The T is always followed by one or more digits.

*Recommended by the Aluminum Association.

†A digit after H represents a specific combination of basic operations, such as H1—strain hardened only. H2—strain hardened and partly annealed, and H3—strain hardened and stabilized. A second digit indicates the degree of strain hardening, which ranges from 0 for annealing to 9 in the order of increasing tensile strength.

‡A digit after T indicates a type of heat treatment, which may include cooling, cold working, and aging.

There are economic advantages in selecting structural aluminum shapes more efficient for specific purposes than the customary ones. For example, sections such as hollow tubes, shapes with stiffening lips on outstanding flanges, and stiffened panels can be formed by extrusion.

Aluminum alloys generally weigh about 170 lb/ft^3, about one-third that of structural steel. The modulus of elasticity in tension is about 10,000 ksi, compared with 29,000 ksi for structural steel. Poisson's ratio may be taken as 0.50. The coefficient of thermal expansion in the 68 to 212°F range is about 0.000013 $in/in \cdot °F$, about double that of structural steel.

Alloy 6061-T6 is often used for structural shapes and plates. ASTM B308 specifies a minimum tensile strength of 38 ksi, minimum tensile yield strength of 35 ksi, and minimum elongation in 2 in of 10%, but 8% when the thickness is less than ¼ in.

The preceding data indicate that, because of the low modulus of elasticity, aluminum members have good energy absorption. Where stiffness is important, however, the effect of the low modulus should be taken into account. Specific data for an application should be obtained from the producers.

4.54 WELDING AND BRAZING OF ALUMINUM

Weldability and brazing properties of aluminum alloys depend heavily on their composition and heat treatment. Most of the wrought alloys can be brazed and welded, but sometimes only by special processes. The strength of some alloys

TABLE 4.22 Finishes for Aluminum and Aluminum Alloys

Types of finish	Designation*
Mechanical finishes:	
As fabricated	M1*Y*
Buffed	M2*Y*
Directional textured	M3*Y*
Nondirectional textured	M4*Y*
Chemical finishes:	
Nonetched cleaned	C1*Y*
Etched	C2*Y*
Brightened	C3*Y*
Chemical conversion coatings	C4*Y*
Coatings:	
Anodic	
General	A1*Y*
Protective and decorative (less than 0.4 mil thick)	A2*Y*
Architectural Class II (0.4–0.7 mil thick)	A3*Y*
Architectural Class I (0.7 mil or more thick)	A4*Y*
Resinous and other organic coatings	R1*Y*
Vitreous coatings	V1*Y*
Electroplated and other metallic coatings	E1*Y*
Laminated coatings	L1*Y*

* *Y* represents digits (0, 1, 2, . . . 9) or *X* (to be specified) that describe the surface, such as specular, satin, matte, degreased, clear anodizing or type of coating.

depends on heat treatment after welding. Alloys heat treated and artificially aged are susceptible to loss of strength at the weld, because weld is essentially cast. For this reason, high-strength structural alloys are commonly fabricated by riveting or bolting, rather than by welding.

Brazing is done by furnace, torch, or dip methods. Successful brazing is done with special fluxes.

Inert-gas shielded-arc welding is usually used for welding aluminum alloys. The inert gas, argon or helium, inhibits oxide formation during welding. The electrode used may be consumable metal or tungsten. The gas metal arc is generally preferred for structural welding, because of the higher speeds that can be used. The gas tungsten arc is preferred for thicknesses less than ½ in.

Butt-welded joints of annealed aluminum alloys and non-heat-treatable alloys have nearly the same strength as the parent metal. This is not true for strain-hardened or heat-tempered alloys. In these conditions, the heat of welding weakens the metal in the vicinity of the weld. The tensile strength of a butt weld of alloy 6061-T6 may be reduced to 24 ksi, about two-thirds that of the parent metal. Tensile yield strength of such butt welds may be only 15 to 20 ksi, depending on metal thickness and type of filler wire used in welding.

Fillet welds similarly weaken heat-treated alloys. The shear strength of alloy 6061-T6 decreases from about 27 ksi to 17 ksi or less for a fillet weld.

Welds should be made to meet the requirements of the American Welding Society, ‘‘Structural Welding Code—Aluminum,’’ AWS D1.2.

4.55 BOLTED AND RIVETED ALUMINUM CONNECTIONS

Aluminum connections also may be bolted or riveted. Bolted connections are bearing type. Slip-critical connections, which depend on the frictional resistance of joined parts created by bolt tension, are not usually employed because of the relatively low friction and the potential relaxation of the bolt tension over time.

Bolts may be aluminum or steel. Bolts made of aluminum alloy 7075-T73 have a minimum expected shear strength of 40 ksi. Cost per bolt, however, is higher than that of 2024-T4 or 6061-T6, with tensile strengths of 37 and 27 ksi, respectively. Steel bolts may be used if the bolt material is selected to prevent galvanic corrosion or the steel is insulated from the aluminum. One option is use of stainless steel. Another alternative is to galvanize, aluminize, or cadmium plate the steel bolts.

Rivets typically are made of aluminum alloys. They are usually driven cold by squeeze-type riveters. Alloy 6053-T61, with a shear strength of 20 ksi, is preferred for joining relatively soft alloys, such as 6063-T5, Alloy 6061-T6, with a shear strength of 26 ksi, is usually used for joining 6061-T6 and other relatively hard alloys.

4.56 PREVENTION OF CORROSION OF ALUMINUM

Although aluminum ranks high in the electromotive series of the metals, it is highly corrosion resistant because of the tough, transparent, tenacious film of aluminum oxide that rapidly forms on any exposed surface. It is this corrosion resistance that recommends aluminum for building applications. For most exposures, including industrial and seacoast atmospheres, the alloys normally recommended are adequate, particularly if used in usual thicknesses and if mild pitting is not objectionable.

Pure aluminum is the most corrosion resistant of all and is used alone or as cladding on strong-alloy cores where maximum resistance is wanted. Of the alloys, those containing magnesium, manganese, chromium, or magnesium and silicon in the form of $MgSi_2$ are highly resistant to corrosion. The alloys containing substantial proportions of copper are more susceptible to corrosion, depending markedly on the heat treatment.

Certain precautions should be taken in building. Aluminum is subject to attack by alkalies, and it should therefore be protected from contact with wet concrete, mortar, and plaster. Clear methacrylate lacquers or strippable plastic coatings are recommended for interiors and methacrylate lacquer for exterior protection during construction. Strong alkaline and acid cleaners should be avoided and muriatic acid should not be used on masonry surfaces adjacent to aluminum. If aluminum must be contiguous to concrete and mortar outdoors, or where it will be wet, it should be insulated from direct contact by asphalts, bitumens, felts, or other means. As is true of other metals, atmospheric-deposited dirt must be removed to maintain good appearance.

Electrolytic action between aluminum and less active metals should be avoided, because the aluminum then becomes anodic. If aluminum must be in touch with other metals, the faying surfaces should be insulated by painting with asphaltic or similar paints, or by gasketing. Steel rivets and bolts, for example, should be insulated. Drainage from copper-alloy surfaces onto aluminum must be avoided. Frequently, steel surfaces can be galvanized or cadmium-coated where contact is expected with aluminum. The zinc or cadmium coating is anodic to the aluminum and helps to protect it.

4.57 ALUMINUM BIBLIOGRAPHY

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COPPER AND COPPER-BASED ALLOYS

Copper and its alloys are widely used in the building industry for a large variety of purposes, particularly applications requiring corrosion resistance, high electrical conductivity, strength, ductility, impact resistance, fatigue resistance, or other special characteristics possessed by copper or its alloys. Some of the special characteristics of importance to building are ability to be formed into complex shapes, appearance, and high thermal conductivity, although many of the alloys have low thermal conductivity and low electrical conductivity as compared with the pure metal.

4.58 COPPER

The excellent corrosion resistance of copper makes it suitable for such applications as roofing, flashing, cornices, gutters, downspouts, leaders, fly screens, and similar applications. For roofing and flashing, soft-annealed copper is employed, because it is ductile and can easily be bent into various shapes. For gutters, leaders, downspouts, and similar applications, cold-rolled hard copper is employed, because its greater hardness and stiffness permit it to stand without large numbers of intermediate supports.

Copper and copper-based alloys, particularly the brasses, are employed for water pipe in buildings, because of their corrosion resistance. Electrolytic tough-pitch copper is usually employed for electrical conductors, but for maximum electrical conductivity and weldability, oxygen-free high-conductivity copper is used.

When arsenic is added to copper, it appears to form a tenacious adherent film, which is particularly resistant to pitting corrosion. Phosphorus is a powerful deoxidizer and is particularly useful for copper to be used for refrigerator tubing and other applications where flaring, flanging, and spinning are required. Arsenic and phosphorus both reduce the electrical conductivity of the copper.

For flashing, copper is frequently coated with lead to avoid the green patina formed on copper that is sometimes objectionable when it is washed down over adjacent surfaces, such as ornamental stone. The patina is formed particularly in industrial atmospheres. In rural atmospheres, where industrial gases are absent, the copper normally turns to a deep brown color.

Principal types of copper and typical uses are:

Electrolytic tough pitch (99.90% copper) is used for electrical conductors—bus bars, commutators, etc.; building products—roofing, gutters, etc.; process equipment—kettles, vats, distillery equipment; forgings. General properties are high electrical conductivity, high thermal conductivity, and excellent working ability.

Deoxidized (99.90% copper and 0.025% phosphorus) is used, in tube form, for water and refrigeration service, oil burners, etc.; in sheet and plate form, for welded construction. General properties include higher forming and bending qualities than electrolytic copper. They are preferred for coppersmithing and welding (because of resistance to embrittlement at high temperatures).

4.59 BRASS

A considerable range of brasses is obtainable for a large variety of end uses. The high ductility and malleability of the copper-zinc alloys, or brasses, make them suitable for operations like deep drawing, bending, and swaging. They have a wide range of colors. They are generally less expensive than the high-copper alloys.

Grain size of the metal has a marked effect upon its mechanical properties. For deep drawing and other heavy working operations, a large grain size is required, but for highly finished polished surfaces, the grain size must be small.

Like copper, brass is hardened by cold working. Hardnesses are sometimes expressed as quarter hard, half hard, hard, extra hard, spring, and extra spring, corresponding to reductions in cross section during cold working ranging from approximately 11 to 69%. Hardness is strongly influenced by alloy composition, original grain size, and form (strip, rod, tube, wire).

4.59.1 Plain Brass

Brass compositions range from higher copper content to zinc contents as high as 40% or more. Brasses with less than 36% zinc are plain alpha solid solutions; but Muntz metal, with 40% zinc, contains both alpha and beta phases.

The principal plain brasses of interest in building, and their properties are:

Commercial bronze, 90% (90.0% copper, 10.0% zinc). Typical uses are forgings, screws, weatherstripping, and stamped hardware. General properties include excellent cold working and high ductility.

Red brass, 85% (85.0% copper, 15.0% zinc). Typical uses are dials, hardware, etched parts, automobile radiators, and tube and pipe for plumbing. General properties are higher strength and ductility than copper, and excellent corrosion resistance.

Cartridge brass, 70% (70.0% copper, 30.0% zinc). Typical uses are deep drawing, stamping, spinning, etching, rolling—for practically all fabricating processes—cartridge cases, pins, rivets, eyelets, heating units, lamp bodies and reflectors, electrical sockets, drawn shapes, etc. General properties are best combination of ductility and strength of any brass, and excellent cold-working properties.

Muntz metal (60.0% copper, 40.0% zinc). Typical uses are sheet form, perforated metal, architectural work, condenser tubes, valve stems, and brazing rods. General properties are high strength combined with low ductility.

4.59.2 Leaded Brass

Lead is added to brass to improve its machinability, particularly in such applications as automatic screw machines where a freely chipping metal is required. Leaded brasses cannot easily be cold-worked by such operations as flaring, upsetting, or cold heading. Several leaded brasses of importance in the building field are the following:

High-leaded brass (64.0% copper, 34.0% zinc, 2.0% lead). Typical uses are engraving plates, machined parts, instruments (professional and scientific), nameplates, keys, lock parts, and tumblers. General properties are free machining and good blanking.

Forging brass (60.0% copper, 38.0% zinc, 2.0% lead). Typical uses are hot forging, hardware, and plumbing goods. General properties are extreme plasticity when hot and a combination of good corrosion resistance with excellent mechanical properties.

Architectural bronze (56.5% copper, 41.25% zinc, 2.25% lead). Typical uses are handrails, decorative moldings, grilles, revolving door parts, miscellaneous architectural trim, industrial extruded shapes (hinges, lock bodies, automotive parts). General properties are excellent forging and free-machining properties.

4.59.3 Tin Brass

Tin is added to a variety of basic brasses to obtain hardness, strength, and other properties that would otherwise not be available. Two important alloys are:

Admiralty (71.0% copper, 28.0% zinc, 1.0% tin, 0.05% arsenic). Typical uses are condenser and heat-exchanger plates and tubes, steam-power-plant equipment, chemical and process equipment, and marine uses. General properties are excellent corrosion resistance, combined with strength and ductility.

Manganese bronze (58.5% copper, 39.0% zinc, 1.4% iron, 1.0% tin, 0.1% manganese). Typical uses are forgings, condenser plates, valve stems, and coal screens. General properties are high strength combined with excellent wear resistance.

4.60 NICKEL SILVERS

These are alloys of copper, nickel, and zinc. Depending on the composition, they range in color from a definite to slight pink cast through yellow, green, whitish green, whitish blue, to blue. A wide range of nickel silvers is made, of which only one typical composition will be described. Those that fall in the combined alpha-beta phase of metals are readily hot-worked and therefore are fabricated without difficulty into such intricate shapes as plumbing fixtures, stair rails, architectural shapes, and escalator parts. Lead may be added to improve machining.

Nickel, silver, 18% (A) (65.0% copper, 17.0% zinc, 18.0% nickel). Typical uses are hardware, architectural panels, lighting, electrical and plumbing fixtures. General properties are high resistance to corrosion and tarnish, malleable, and ductile. Color: silver-blue-white.

4.61 CUPRONICKEL

Copper and nickel are alloyed in a variety of compositions of which the high-copper alloys are called the cupronickels. Typical commercial types of cupronickel contain 10 or 30% nickel (Table 4.15):

Cupronickel, 10% (88.5% copper, 10% nickel, 1.5% iron). Recommended for applications requiring corrosion resistance, especially to salt water, as in tubing for condensers, heat exchangers, and formed sheets.

Cupronickel, 30% (70.0% copper, 30.0% nickel). Typical uses are condenser tubes and plates, tanks, vats, vessels, process equipment, automotive parts, meters, refrigerator pump valves. General properties are high strength and ductility and resistance to corrosion and erosion. Color: white-silver.

4.62 BRONZE

Originally, the bronzes were all alloys of copper and tin. Today, the term bronze is generally applied to engineering metals having high mechanical properties and the term brass to other metals. The commercial wrought bronzes do not usually contain more than 10% tin because the metal becomes extremely hard and brittle. When phosphorus is added as a deoxidizer, to obtain sound, dense castings, the alloys are known as phosphor bronzes. The two most commonly used tin bronzes contain 5 or 8% tin. Both have excellent cold-working properties.

4.62.1 Silicon Bronze

These are high-copper alloys containing percentages of silicon ranging from about 1% to slightly more than 3%. In addition, they generally contain one or more of the four elements, tin, manganese, zinc, and iron. A typical one is high-silicon bronze, type A.

High-silicon bronze, A (96.0% copper, 3.0% silicon, 1.0% manganese). Typical users are tanks—pressure vessels, vats; weatherstrips, forgings. General properties are corrosion resistance of copper and mechanical properties of mild steel.

4.62.2 Aluminum Bronze

Like aluminum, these bronzes form an aluminum oxide skin on the surface, which materially improves resistance to corrosion, particularly under acid conditions. Since the color of the 5% aluminum bronze is similar to that of 18-carat gold, it is used for costume jewelry and other decorative purposes. Aluminum-silicon bronzes are used in applications requiring high tensile properties in combination with good corrosion resistance in such parts as valves, stems, air pumps, condenser bolts, and similar applications. Their wear-resisting properties are good; consequently, they are used in slide liners and bushings.

4.63 COPPER BIBLIOGRAPHY

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G. S. Brady and H. R. Clauser, “Materials Handbook,” 13th ed., and J. H. Callender, “Time-Saver Standards for Architectural Design Data,” 6th ed., McGraw-Hill Publishing Company, New York.

LEAD AND LEAD-BASED ALLOYS

Lead is used primarily for its corrosion resistance. Lead roofs 2000 years old are still intact.

4.64 APPLICATIONS OF LEAD

Exposure tests indicate corrosion penetrations of sheet lead ranging from less than 0.0001 in to less than 0.0003 in in 10 years in atmospheres ranging from mild rural to severe industrial and seacoast locations. Sheet lead is therefore used for roofing, flashing, spandrels, gutters, and downspouts.

Because the green patina found on copper may wash away sufficiently to stain the surrounding structure, lead-coated copper is frequently employed. ASTM B101-78 covers two classes, defined by the weight of coating.

Lead pipe should not be used for the transport of drinking water. Distilled and very soft waters slowly dissolve lead and may cause cumulative lead poisoning. Hard waters apparently deposit a protective coating on the wall of the pipe and little or no lead is subsequently dissolved in the water.

Principal alloying elements used with building leads are antimony (for hardness and strength) and tin. But copper, arsenic, bismuth, nickel, zinc, silver, iron, and manganese are also added in varying proportions.

Soft solders consist of varying percentages of lead and tin. For greater hardness, antimony is added, and for higher-temperature solders, silver is added in small amounts. ASTM Standard B32 specifies properties of soft solders.

Low-melting alloys and many bearing metals are alloys of lead, bismuth, tin, cadmium, and other metals including silver, zinc, indium, and antimony. The fusible links used in sprinkler heads and fire-door closures, made of such alloys, have a low melting point, usually lower than the boiling point of water. Yield (softening) temperatures range from 73 to 160°F and melting points from about 80 to 480°F, depending on the composition.

4.65 LEAD BIBLIOGRAPHY

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NICKEL AND NICKEL-BASED ALLOYS

Nickel is used mostly as an alloying element with other metals, but it finds use in its own right, largely as electroplate or as cladding metal. Among the principal high-nickel alloys are Monel and Inconel. The nominal compositions of these metals are given in Table 4.23

4.66 PROPERTIES OF NICKEL AND ITS ALLOYS

Nickel is resistant to alkaline corrosion under nonoxidizing conditions but is corroded by oxidizing acids and oxidizing salts. It is resistant to fatty acids, other mildly acid conditions, such as food processing and beverages, and resists oxidation at temperatures as high as 1600°F.

Monel is widely used in kitchen equipment. It is better than nickel in reducing conditions like warm unaerated acids, and better than copper under oxidizing conditions, such as aerated acids, alkalies, and salt solutions. It is widely used for handling chlorides of many kinds.

Inconel is almost completely resistant to corrosion by food products, pharmaceuticals, biologicals, and dilute organic acids. It is superior to nickel and Monel

TABLE 4.23 Composition of Nickel Alloys

	Nickel alloy, low-carbon NO2201	Nickel alloy NO2200	Monel NO4400	Inconel NO6600	70–30 cupro-nickel C71500	90–10 cupro-nickel C70600
Content	ASTM B160	ASTM B160	ASTM B127	ASTM B168	ASTM B171	ASTM B171
Carbon	0.02	0.15	0.2	0.15 max		
Manganese	0.35	0.35	2.00 max	1.0 max	1.0 max	1.0 max
Sulfur	0.01	0.01	0.024 max	0.015 max		
Silicon	0.35	0.35	0.5	0.5 max		
Chromium				14–17		
Nickel	99 min	99 min	63–70	72 min	29–33	9–11
Copper	0.25	0.25	Remainder	0.5 max	65 min	86.5 min
Iron	0.40 max	0.40 max	2.5 max	6–10	0.40–1.0	1.0–1.8
Lead					0.05 max	0.05 max
Zinc					1.0	1.0

in resisting oxidizing acid salts like chromates and nitrates but is not resistant to ferric, cupric, or mercuric chlorides. It resists scaling and oxidation in air and furnace atmospheres at temperatures up to 2000°F.

4.67 NICKEL BIBLIOGRAPHY

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PLASTICS

The synonymous terms plastics and synthetic resins denote synthetic organic high polymers, all of which are plastic at some stage in their manufacture. Plastics fall into two large categories—thermoplastic and thermosetting materials.

4.68 GENERAL PROPERTIES OF PLASTICS

Thermoplastics may be softened by heating and hardened by cooling any number of times. Thermosetting materials are either originally soft or liquid, or they soften once upon heating; but upon further heating, they harden permanently. Some thermosetting materials harden by an interlinking mechanism in which water or other by-product is given off, by a process called condensation; but others, like the unsaturated polyesters, harden by a direct interlinking of the basic molecules without release of a by-product.

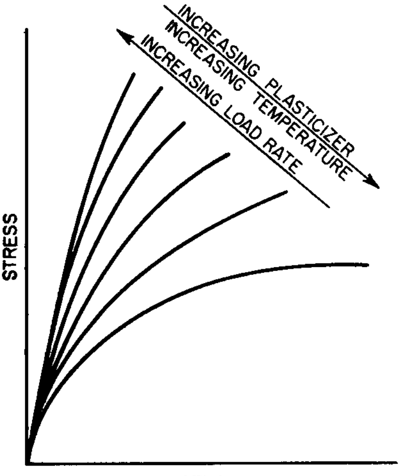

FIGURE 4.5 Stress-strain diagram shows the influence of temperature, plasticizer, and rate of loading on behavior of plastics.

Most plastics are modified with plasticizers, fillers, or other ingredients. Consequently, each base material forms the nucleus for a large number of products having a wide variety of properties. This section can only indicate generally the range of properties to be expected.

Because plastics are quite different in their composition and structure from other materials, such as metals, their behavior under stress and under other conditions is likely to be different from other materials. Just as steel and lead are markedly different and are used for different applications, so the various plastics materials—some hard and brittle, others soft and extensible—must be designed on different bases and used in different ways. Some plastics show no yield point, because they fail before a yield point can be reached. Others have a moderately high elastic range, followed by a highly plastic range. Still others are highly extensible and are employed at stresses far beyond the yield point.

More than many other materials, plastics are sensitive to temperature and to the rate and time of application of load. How these parameters influence the properties is indicated in a general way in Fig. 4.5, which shows that for many plastics in increase in temperature, increase in plasticizer content, and decrease in rate of load application mean an increase in strain to fracture, accompanied by a decrease in maximum stress. This viscoelastic behavior, combining elastic and viscous or plastic reaction to stress, is unlike the behavior of materials which are traditionally considered to behave only elastically.

4.69 FILLERS AND PLASTICIZERS

Fillers are commonly added, particularly to the thermosetting plastics, to alter their basic characteristics. For example, wood flour converts a hard, brittle resin, difficult to handle, into a cheaper, more easily molded material for general purposes. Asbestos fibers provide better heat resistance; mica gives better electrical properties; and a variety of fibrous materials, such as chopped fibers, chopped fabric, and chopped tire cords, increase the strength and impact properties.

Plasticizers are added to many thermoplastics, primarily to transform hard and rigid materials into a variety of forms having varying degrees of softness, flexibility, and strength. In addition, dyes or pigments, stabilizers, and other products may be added.

4.70 MOLDING AND FABRICATING METHODS FOR PLASTICS

Both thermosetting and thermoplastic molding materials are formed into final shape by a variety of molding and fabricating methods.

Thermosetting materials are commonly formed by placing molding powder or molded preform in heated dies and compressing under heat and pressure into the final infusible shape. Or they are formed by forcing heat-softened material into a heated die for final forming into the hard infusible shape.

Thermoplastics are commonly formed by injection molding, that is, by forcing soft, hot plastic into a cold die, where it hardens by cooling. Continuous profiles of thermoplastic materials are made by extrusion. Thermoplastic sheets, especially transparent acrylics, are frequently formed into final shape by heating and then blowing to final form under compressed air or by drawing a partial vacuum against the softened sheet.

Foamed plastics are employed for thermal insulation in refrigerators, buildings, and many other applications. In buildings, plastics are either prefoamed into slabs, blocks, or other appropriate shapes, or they are foamed in place.

Prefoamed materials, such as polystyrene, are made by adding a blowing agent and extruding the mixture under pressure and at elevated temperatures. As the material emerges from the extruder, it expands into a large ‘‘log’’ that can be cut into desired shapes. The cells are ‘‘closed’’; that is, they are not interconnecting and are quite impermeable.

Foamed-in-place plastics are made with pellets or liquids. The pellets, made, for example, of polystyrene, are poured into the space to be occupied, such as a mold, and heated, whereupon they expand and occupy the space. The resulting mass may be permeable between pellets. Liquid-based foams, exemplified by polyurethane, are made by mixing liquid ingredients and immediately casting the mixture into the space to be occupied. A quick reaction results in a foam that rises and hardens by a thermosetting reaction. When blown with fluorocarbon gases, such forms have exceptionally low thermal conductivities.

All the plastics can be machined, if proper allowance is made for the properties of the materials.

Plastics are often combined with sheet or mat stocks, such as paper, cotton muslin, glass fabric, glass filament mats, nylon fabric, and other fabrics, to provide laminated materials in which the properties of the combined plastic and sheet stock are quite different from the properties of either constituent by itself. Two principal varieties of laminates are commonly made: (1) High-pressure laminates employing condensation-type thermosetting materials, which are formed at elevated temperatures and pressures. (2) Reinforced plastics employing unsaturated polyesters and epoxides, from which no by-products are given off, and consequently, either low pressures or none at all may be required to form combinations of these materials with a variety of reinforcing agents, like glass fabric or mat.

4.71 THERMOSETTING PLASTICS

General properties of thermosetting plastics are described in Art. 4.68. Following are properties of several thermosetting plastics used in buildings:

Phenol Formaldehyde. These materials provide the greatest variety of thermosetting molded plastic articles. They are used for chemical, decorative, electrical, mechanical, and thermal applications of all kinds. Hard and rigid, they change slightly, if at all, on aging indoors but, on outdoor exposure, lose their bright surface gloss. However, the outdoor-exposure characteristics of the more durable formulations are otherwise generally good. Phenol formaldehydes have good electrical properties, do not burn readily, and do not support combustion. They are strong, light in weight, and generally pleasant to the eye and touch, although light colors by and large are not obtainable because of the fairly dark-brown basic color of the resin. They have low water absorption and good resistance to attack by most commonly found chemicals.

Epoxy and Polyester Casting Resins. These are used for a large variety of purposes. For example, electronic parts with delicate components are sometimes cast completely in these materials to give them complete and continuous support, and resistance to thermal and mechanical shock. Some varieties must be cured at elevated temperatures; others can be formulated to be cured at room temperatures. One of the outstanding attributes of the epoxies is their excellent adhesion to a variety of materials, including such metals as copper, brass, steel, and aluminum.

Polyester Molding Materials. When compounded with fibers, particularly glass fibers, or with various mineral fillers, including clay, the polyesters can be formulated into putties or premixes that are easily compression- or transfer-molded into parts having high impact resistance. Polyesters are often used in geotextiles (Art. 6.11.2).

Melamine Formaldehyde. These materials are unaffected by common organic solvents, greases, and oils, as well as most weak acids and alkalies. Their water absorption is low. They are insensitive to heat and are highly flame-resistant, depending on the filler. Electrical properties are particularly good, especially resistance to arcing. Unfilled materials are highly translucent and have unlimited color possibilities. Principal fillers are alpha cellulose for general-purpose compounding; minerals to improve electrical properties, particularly at elevated temperatures; chopped fabric to afford high shock resistance and flexural strength; and cellulose, mainly for electrical purposes.

Cellulose Acetate Butyrate. The butyrate copolymer is inherently softer and more flexible than cellulose acetate and consequently requires less plasticizer to achieve a given degree of softness and flexibility. It is made in the form of clear transparent sheet and film, or in the form of molding powders, which can be molded by standard injection-molding procedures into a wide variety of applications. Like the other cellulosics, this material is inherently tough and has good impact resistance. It has infinite colorability, like the other cellulosics. Cellulose acetate butyrate tubing is used for such applications as irrigation and gas lines.

Cellulose Nitrate. One of the toughest of the plastics, cellulose nitrate is widely used for tool handles and similar applications requiring high impact strength. The high flammability requires great caution, particularly in the form of film. Most commercial photographic film is cellulose nitrate as opposed to safety film.

Polyurethane. This plastic is used in several ways in building. As thermal insulation, it is used in the form of foam, either prefoamed or foamed in place. The latter is particularly useful in irregular spaces. When blown with fluorocarbons, the foam has an exceptionally low *K*-factor and is, therefore, widely used in thin-walled refrigerators. Other uses include field-applied or baked-on clear or colored coatings and finishes for floors, walls, furniture, and casework generally. The rubbery form is employed for sprayed or troweled-on roofing, and for gaskets and calking compounds.

Urea Formaldehyde. Like the melamines, these offer unlimited translucent to opaque color possibilities, light-fastness, good mechanical and electrical properties, and resistance to organic solvents as well as mild acids and alkalies. Although there is no swelling or change in appearance, the water absorption of urea formaldehyde is relatively high, and it is therefore not recommended for applications involving long exposure to water. Occasional exposure to water is without deleterious effect. Strength properties are good, although special shock-resistant grades are not made.

Silicones. Unlike other plastics, silicones are based on silicon rather than carbon. As a consequence, their inertness and durability under a wide variety of conditions are outstanding. As compared with the phenolics, their mechanical properties are poor, and consequently glass fibers are added. Molding is more difficult than with other thermosetting materials. Unlike most other resins, they may be used in continuous operations at 400°F; they have very low water absorption; their dielectric properties are excellent over an extremely wide variety of chemical attack; and under outdoor conditions their durability is particularly outstanding. In liquid solutions, silicones are used to impart moisture resistance to masonry walls and to fabrics. They also form the basis for a variety of paints and other coatings capable of maintaining flexibility and inertness to attack at high temperatures in the presence of ultraviolet sunlight and ozone. Silicone rubbers maintain their flexibility at much lower temperatures than other rubbers.

4.72 THERMOPLASTIC RESINS

Materials under this heading in general can be softened by heating and hardened by cooling.

Acrylics. In the form of large transparent sheets, these are used in aircraft enclosures and building construction. Although not so hard as glass, they have perfect clarity and transparency. Among the most resistant of the transparent plastics to sunlight and outdoor weathering, they possess an optimum combination of flexibility and sufficient rigidity with resistance to shattering. A wide variety of transparent, translucent, and opaque colors can be produced. The sheets are readily formed to complex shapes. They are used for such applications as transparent windows, outdoor and indoor signs, parts of lighting equipment, decorative and functional automotive parts, reflectors, household-appliance parts, and similar applications. They can be used as large sheets, molded from molding powders, or cast from the liquid monomer.

***Acrylonitrile-Butadiene-Styrene* (*ABS*).** This three-way copolymer provides a family of tough, hard, chemically resistant resins with many grades and varieties, depending on variations in constituents. The greatest use is for pipes and fittings, especially drain-waste-vent (DWV). Other uses include buried sewer and water lines, mine pipe, well casings, conduit, and appliance housings.

Polyethylene. In its unmodified form, this is a flexible, waxy, translucent plastic. It maintain flexibility at very low temperatures, in contrast with many other thermoplastic materials.

Polyethylene may be provided as low-density, or standard, or as high-density or linear material. High-density polyethylene has greater strength and stiffness, withstands somewhat higher temperatures, and has a more sharply defined softening temperature range. The heat-distortion point of the low-density polyethylenes is low; these plastics are not recommended for uses above 150°F. Unlike most plastics, polyethylene is partly crystalline. It is highly inert to solvents and corrosive chemicals of all kinds at ordinary temperatures. Usually low moisture permeability and absorption are combined with excellent electrical properties. Its density is lower than that of any other commercially available nonporous plastic. It is widely used as a primary insulating material on wire and cable and has been used as a replacement for the lead jacket in communication cables and other cables. It is widely used also in geogrids, geonets, and geomembranes (Art. 6.11) and as corrosionproof lining for tanks and other chemical equipment.

Polypropylene. This polyolefin is similar in many ways to its counterpart, polyethylene, but is generally harder, stronger, and more temperature-resistant. It finds a great many uses, among them piping, geotextiles, and geogrids (Art. 6.11), and complete water cisterns for water closets in plumbing systems.

Polycarbonate. Excellent transparency, high impact resistance, and good resistance to weathering combine to recommend this plastic for safety glazing and for general illumination and shatter-resistant fixtures. It is available in large, clear, tinted, and opaque sheets that can be formed into shells, domes, globes, and other forms. It can be processed by standard molding methods.

Polytetrafluorethylene. This is a highly crystalline liner-type polymer, unique among organic compounds in its chemical inertness and resistance to change at high and low temperatures. Its electrical properties are excellent. Its outstanding property is extreme resistance to attack by corrosive agents and solvents of all kinds. Waxy and self-lubricating, polytetrafluoroethylene is used in buildings where resistance to extreme conditions or low friction is desired. In steam lines, for example, supporting pads of this plastic permit the lines to slide easily over the pads. The temperatures involved have little or no effect. Other low-friction applications include, for example, bearings for girders and trusses. Mechanical properties are only moderately high, and reinforcement may be necessary to prevent creep and squeeze-out under heavy loads. These fluorocarbons are difficult to wet; consequently, they are often used as parting agents, or where sticky materials must be handled.

Polyvinylfluoride. This has much of the superior inertness to chemical and weathering attack typical of the fluorocarbons. Among other uses, it is used as thin-film overlays for building boards to be exposed outdoors.

Polyvinyl Formal and Polyvinyl Butyral. Polyvinyl formal resins are principally used as a base for tough, water-resistant insulating enamel for electric wire. Polyvinyl butyral is the tough interlayer in safety glass. In its cross-linked and plasticized form, polyvinyl butyral is extensively used in coating fabrics for raincoats, upholstery, and other heavy-duty moisture-resistant applications.

Vinyl Chloride Polymers and Copolymers. Polyvinyl chloride is naturally hard and rigid but can be plasticized to any required degree of flexibility as in raincoats and shower curtains. Copolymers, including vinyl chloride plus vinyl acetate, are naturally flexible without plasticizers. Nonrigid vinyl plastics are widely used as insulation and jacketing for electric wire and cable because of their electrical properties and their resistance to oil and water. Thin films are used in geomembranes (Art. 6.11). Vinyl chlorides also are used for floor coverings in the form of tile and sheet because of their abrasion resistance and relatively low water absorption. The rigid materials are used for tubing, pipe, and many other applications where their resistance to corrosion and action of many chemicals, especially acids and alkalies, recommends them. They are attacked by a variety of organic solvents, however. Like all thermoplastics, they soften at elevated temperatures.

Vinylidene Chloride. This material is highly resistant to most inorganic chemicals and to organic solvents generally. It is impervious to water on prolonged immersion, and its films are highly resistant to moisture-vapor transmission. It can be sterilized, if not under load, in boiling water. It is used as pipe for transporting chemicals and geomembranes (Art. 6.11).

Nylon. Molded nylon is used in increasing quantities for impact and high resistance to abrasion. It is employed in small gears, cams, and other machine parts, because even when unlubricated they are highly resistant to wear. Its chemical resistance, except to phenols and mineral acids, is excellent. Extruded nylon is coated onto electric wire, cable, and rope for abrasion resistance. Applications like hammerheads indicate its impact resistance.

Polystyrene. This is one of the lightest of the presently available commercial plastics. It is relatively inexpensive, easily molded, has good dimensional stability, and good stability at low temperatures; it is brilliantly clear when transparent and has an infinite range of colors. Water absorption is negligible even after long immersion. Electrical characteristics are excellent. It is resistant to most corrosive chemicals, such as acids, and to a variety of organic solvents, although it is attacked by others. Polystyrenes as a class are considerably more brittle and less extensible than many other thermoplastic materials, but these properties are markedly improved in copolymers. Under some conditions, they have a tendency to develop fine cracks, known as craze marks, on exposure, particularly outdoors. This is true of many other thermoplastics, especially when highly stressed. It is widely used in synthetic rubbers.

4.73 ELASTOMERS, OR SYNTHETIC RUBBERS

Rubber for construction purposes is both natural and synthetic. Natural rubber, often called crude rubber in its unvulcanized form, is composed of large complex molecules of isoprene. Synthetic rubbers, also known as elastomers, are generally rubber-like only in their high elasticity. The principal synthetic rubbers are the following:

GR-S is the one most nearly like crude rubber and is the product of styrene and butadiene copolymerization. It is the most widely used of the synthetic rubbers. It is not oil-resistant but is widely used for tires and similar applications.

Nitril is a copolymer of acrylonitrile and butadiene. Its excellent resistance to oils and solvents makes it useful for fuel and solvent hoses, hydraulic-equipment parts, and similar applications.

Butyl is made by the copolymerization of isobutylene with a small proportion of isoprene or butadiene. It has the lowest gas permeability of all the rubbers and consequently is widely used for making inner tubes for tires and other applications in which gases must be held with a minimum of diffusion. It is used for gaskets in buildings.

Neoprene is made by the polymerization of chloroprene. It has very good mechanical properties and is particularly resistant to sunlight, heat, aging, and oil; it is therefore used for making machine belts, gaskets, oil hose, insulation on wire cable, and other applications to be used for outdoor exposure, such as roofing, and gaskets for building and glazing.

Sulfide rubbers—the polysulfides of high molecular weight—have rubbery properties, and articles made from them, such as hose and tank linings and glazing compounds, exhibit good resistance to solvents, oils, ozone, low temperature, and outdoor exposure.

Silicone rubber, which also is discussed in Art. 4.71, when made in rubbery consistency forms a material exhibiting exceptional inertness and temperature resistance. It is therefore used in making gaskets, electrical insulation, and similar products that maintain their properties at both high and low temperatures.

Additional elastomers include polyethylene, cyclized rubber, plasticized polyvinyl chloride, and polybutene. A great variety of materials enters into various rubber compounds and therefore provide a wide range of properties. In addition, many elastomeric products are laminated structures of rubber-like compounds combined with materials like fabric and metals (Art. 4.76).

COMBINATIONS OF PLASTICS AND OTHER MATERIALS

Plastics often are used as part of a composite construction with other materials. The composites may be in the form of laminates, matrix systems, sandwich structures, or combinations of these.

4.74 HIGH-PRESSURE LAMINATES

Laminated thermosetting products consist of fibrous sheet materials combined with a thermosetting resin, usually phenol formaldehyde or melamine formaldehyde. The commonly used sheet materials are paper, cotton fabric, asbestos paper or fabric, nylon fabric, and glass fabric. The usual form is flat sheet, but a variety of rolled tubes and rods is made.

Decorative Laminates. These high-pressure laminates consist of a base of phenolic resin-impregnated kraft paper over which a decorative overlay, such as printed paper, is applied. Over all this is laid a thin sheet of melamine resin. When the entire assemblage is pressed in a hot-plate press at elevated temperatures and pressures, the various layers are fused together and the melamine provides a completely transparent finish, resistant to alcohol, water, and common solvents. This material is widely used for tabletops, counter fronts, wainscots, and similar building applications. It is customarily bonded to a core of plywood to develop the necessary thickness and strength. In this case, a backup sheet consisting of phenolic resin and paper alone, without the decorative surface, is employed to provide balance to the entire sandwich.

4.75 REINFORCED PLASTICS

These are commonly made with phenolic, polyester, and epoxide resins combined with various types of reinforcing agents, of which glass fibers in the form of mats or fabrics are the most common. Because little or no pressure is required to form large complex parts, rather simple molds can be employed for the manufacture of such things as boat hulls and similar large parts. In buildings, reinforced plastics have been rather widely used in the form of corrugated sheet for skylights and side lighting of buildings, and as molded shells, concrete forms, sandwiches, and similar applications.

These materials may be formulated to cure at ordinary temperatures, or they may require moderate temperatures to cure the resins. Customarily, parts are made by laying up successive layers of the glass fabric or the glass mat and applying the liquid resin to them. The entire combination is allowed to harden at ordinary temperatures, or it is placed in a heated chamber for final hardening. It may be placed inside a rubber bag and a vacuum drawn to apply moderate pressure, or it may be placed between a pair of matching molds and cured under moderate pressure in the molds.

The high impact resistance of these materials combined with good strength properties and good durability recommends them for building applications. When the quantity of reinforcing agent is kept relatively low, a high degree of translucence may be achieved, although it is less than that of the acrylics and the other transparent thermoplastic materials.

Fabrics for Air-Supported Roofs. Principal requirements for fabrics and coatings for air-supported structures are high strip tensile strength in both warp and fill directions, high tear resistance, good coating adhesion, maximum weathering resistance, maximum joint strength, good flexing resistance, and good flame resistance. Translucency may or may not be important, depending on the application. The most commonly used fabrics are nylon, polyester, and glass. Neoprene and Hypalon have commonly been employed for military and other applications where opacity is desired. For translucent application, vinyl chloride and fluorocarbon polymers are more common. Careful analysis of loads and stresses, especially dynamic wind loads, and means of joining sections and attaching to anchorage is required.

4.76 LAMINATED RUBBER

Rubber is often combined with various textiles, fabrics, filaments, and metal wire to obtain strength, stability, abrasion resistance, and flexibility. Among the laminated materials are the following:

V Belts. These consist of a combination of fabric and rubber, frequently combined with reinforcing grommets of cotton, rayon, steel, or other high-strength material extending around the central portion.

Flat Rubber Belting. This laminate is a combination of several plies of cotton fabric or cord, all bonded together by a soft-rubber compound.

Conveyor Belts. These, in effect, are moving highways used for transporting such material as crushed rock, dirt, sand, gravel, slag, and similar materials. When the belt operates at a steep angle, it is equipped with buckets or similar devices and becomes an elevator belt. A typical conveyor belt consists of cotton duct plies alternated with thin rubber plies; the assembly is wrapped in a rubber cover, and all elements are united into a single structure by vulcanization. A conveyor belt to withstand extreme conditions is made with some textile or metal cords instead of the woven fabric. Some conveyor belts are especially arranged to assume a trough form and made to stretch less than similar all-fabric belts.

Rubber-Lined Pipes, Tanks, and Similar Equipment. The lining materials include all the natural and synthetic rubbers in various degrees of hardness, depending on the application. Frequently, latex rubber is deposited directly from the latex solution onto the metal surface to be covered. The deposited layer is subsequently vulcanized. Rubber linings can be bonded to ordinary steel, stainless steel, brass, aluminum, concrete, and wood. Adhesion to aluminum is inferior to adhesion to steel. Covering for brass must be compounded according to the composition of the metal.

Rubber Hose. Nearly all rubber hose is laminated and composed of layers of rubber combined with reinforcing materials like cotton duck, textile cords, and metal wire. Typical hose consists of an inner rubber lining, a number of intermediate layers consisting of braided cord or cotton duck impregnated with rubber, and outside that, several more layers of fabric, spirally wound cord, spirally wound metal, or in some cases, spirally wound flat steel ribbon. Outside of all this is another layer of rubber to provide resistance to abrasion. Hose for transporting oil, water, wet concrete under pressure, and for dredging purposes is made of heavy-duty laminated rubber.

Vibration Insulators. These usually consist of a layer of soft rubber bonded between two layers of metal. Another type of insulated consists of a rubber tube or cylinder vulcanized to two concentric metal tubes, the rubber being deflected in shear. A variant of this consists of a cylinder of soft rubber vulcanized to a tubular or solid steel core and a steel outer shell, the entire combination being placed in torsion to act as a spring. Heavy-duty mounts of this type are employed on trucks, buses, and other applications calling for rugged construction.

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PORCELAIN-ENAMELED PRODUCTS

Porcelain enamel, also known as vitreous enamel, is an aluminum-silicate glass, which is fused to metal under high heat. Porcelain-enameled metal is used for indoor and outdoor applications because of its hardness, durability, washability, and color possibilities. For building purposes, porcelain enamel is applied to sheet metal and cast iron, the former for a variety of purposes including trim, plumbing, and kitchen fixtures, and the latter almost entirely for plumbing fixtures. Most sheet metal used for porcelain enameling is steel—low in carbon, manganese, and other elements. Aluminum is also used for vitreous enamel.

4.78 PORCELAIN ENAMEL ON METAL

Low-temperature softening glasses must be employed, especially with sheet metal, to avoid the warping and distortion that would occur at high temperatures. To obtain lower softening temperatures than would be attainable with high-silica glasses, boron is commonly added. Fluorine may replace some of the oxygen, and lead may also be added to produce easy-flowing brilliant enamels; but lead presents an occupational health hazard.

Composition of the enamel is carefully controlled to provide a coefficient of thermal expansion as near that of the base metal as possible. If the coefficient of the enamel is greater than that of the metal, cracking and crazing are likely to occur, but if the coefficient of the enamel is slightly less, it is lightly compressed upon cooling, a desirable condition because glass is strong in compression.

To obtain good adhesion between enamel and metal, one of the so-called transition elements used in glass formulation must be employed. Cobalt is favored. Apparently, the transition elements promote growth of iron crystals from base metal into the enamel, encourage formation of an adherent oxide coating on the iron, which fuses to the enamel, or develop polar chemical bonds between metal and glass.

Usually, white or colored opaque enamels are desired. Opacity is promoted by mixing in, but not dissolving, finely divided materials possessing refractive indexes widely different from the glass. Tin oxide, formerly widely used, has been largely displaced by less expensive and more effective titanium and zirconium compounds. Clay adds to opacity. Various oxides are included to impart color.

Most enameling consists of a ground coat and one or two cover coats fired on at slightly lower temperatures; but one-coat enameling of somewhat inferior quality can be accomplished by first treating the iron surface with soluble nickel salts.

The usual high-soda glasses used to obtain low-temperature softening enamels are not highly acid-resistant and therefore stain readily and deeply when iron-containing water drips on them. Enamels highly resistant to severe staining conditions must be considerably harder; i.e., have higher softening temperatures and therefore require special techniques to avoid warping and distorting of the metal base.

Interiors of refrigerators are often made of porcelain-enameled steel sheets for resistance to staining by spilled foods, whereas the exteriors are commonly baked-on synthetic-resin finishes.

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ASPHALT AND BITUMINOUS PRODUCTS

Asphalt, because of its water-resistant qualities and good durability, is used for many building applications to exclude water, provide a cushion against vibration and expansion, and serve as pavement.

4.80 ASPHALTS FOR DAMPPROOFING AND WATERPROOFING

Dampproofing is generally only a mopped-on coating, whereas waterproofing usually is a built-up coating of one or more plies. Bituminous systems used for dampproofing and waterproofing may be hot applied or cold applied.

ASTM D449, ‘‘Asphalt Used in Dampproofing and Waterproofing,’’ specifies three types of asphalt. Type I, a soft, adhesive, easy-flowing, self-healing bitumen, is intended for use for underground construction, such as foundations, or where similar moderate temperature conditions exist. The softening point of Type I may range from 115 to 140°F. Type II may be used above ground; for example, on retaining walls or where temperatures will not exceed 122°F. The softening point of Type II may range from 145 to 170°F.

D449 asphalts are suitable for use with an asphalt primer meeting the requirements of ASTM D41. In construction of membrane waterproofing systems with these asphalts, felts should conform to ASTM D226 or D250, fabrics to D173, D1327, or D1668, and asphalt-impregnated glass mats to D2178.

For cold-applied systems, asphalt emulsions or cut-back asphalt mastic reinforced with glass fabric may be used. ASTM D1187 specifies asphalt-based emulsions for protective coatings for metal. D491 contains requirements for asphalt mastic for use in waterproofing building floors but not intended as pavement. The mastic is a mixture of asphalt cement, mineral filler, and mineral aggregate. D1668 covers glass fabric for roofing and waterproofing membranes.

4.81 BITUMINOUS ROOFING

Hot asphalt or coal tar are used for conventional built-up roofing. The bitumens are heated to a high enough temperature to fuse with saturant bitumen in roofing felts, thus welding the plies together. The optimum temperature at the point of application for achieving complete fusion, optimum mopping properties, and the desirable interply mopping weight is called the equiviscous temperature (EVT). Information on EVT should be obtained from the manufacturer.

4.81.1 Built-Up Roofing

For constructing built-up roofing, four grades of asphalt are recognized (ASTM D312): Type I, for inclines up to ½ in/ft; Type II, for inclines up to 1½ in/ft; Type III, for inclines up to 3 in/ft; and Type IV, suited for inclines up to 6 in/ft, generally in areas with relatively high year-round temperatures. Types I through IV may be either smooth or surfaced with slag or gravel. Softening ranges are 135 to 150°F, 158 to 176°F, 180 to 200°F and 210 to 225°F, respectively. Heating of the asphalts should not exceed the flash point, the finished blowing temperature, or 475°F for Type I, 500°F for Type II, 525°F for Types III and IV.

Coal-tar pitches for roofing, dampproofing, and waterproofing are of three types (ASTM D450): Type I, for built-up roofing systems; Type II, for dampproofing and membranes waterproofing systems; Type III, for built-up roofing, but containing less volatiles than Type I. Softening ranges are 126 to 140°F, 106 to 126°F, and 133 to 147°F, respectively.

4.81.2 Roofing Felts

For built-up waterproofing and roofing, types of membranes employed include felt (ASTM D226, D227) and cotton fabrics (ASTM D173). Felts are felted sheets of inorganic or organic fibers saturated with asphalt or coal tar conforming to ASTM D312 and D450.

Standard asphalt felts weigh 15, 20, or 30 lb per square (100 ft^2), and standard coal-tar felts weigh 13 lb per square.

Cotton fabrics are open-weave materials weighing at least 3½ $\mathrm{oz/yd}^2$ before saturation, with thread counts of 24 to 32 per inch. The saturants are either asphalts or coal tars. The saturated fabrics must weigh at least 10 $\mathrm{oz/yd}^2$.

4.81.3 Roll Roofing

Asphalt roll roofing, shingles, and siding consist basically of roofing felt, first uniformly impregnated with hot asphaltic saturant and then coated on each side with at least one layer of a hot asphaltic coating and compounded with a water-insoluble mineral filler. The bottom or reverse side, in each instance, is covered with some suitable material, like powdered mica, to prevent sticking in the package or roll.

Granule-surfaced roll roofing (ASTM D249) is covered uniformly on the weather side with crushed mineral granules, such as slate. Minimum weight of the finished roofing should be 81 to 83 lb per square (100 ft^2), and the granular coating should weigh at least 18.5 lb per square.

Roll roofing (ASTM 224), surfaced with powdered talc or mica, is made in two grades, 39.8 and 54.6 lb per square, of which at least 18 lb must be the surfacing material.

4.82 ASPHALT SHINGLES

There are three standard types: Type I, uniform or nonuniform thickness; Type II, thick butt; and Type III, uniform or nonuniform thickness (ASTM D225). Average weights must be 95 lb per square (100 ft^2). For types I and III, the weather-side coating must weigh 23.0 lb per square; for Type II, 30.0 lb per square. The material in these shingles is similar to that in granule-surfaced roll roofing.

4.83 ASPHALT MASTICS AND GROUTS

Asphalt mastics used for waterproofing floors and similar structures, but not intended for pavement, consist of mixtures of asphalt cement, mineral filler, and mineral aggregate, which can be heated at about 400°F to a sufficiently soft condition to be poured and troweled into place. The raw ingredients may be mixed on the job or may be premixed, formed into cakes, and merely heated on the job (ASTM D491).

Bituminous grouts are suitable for waterproofing above or below ground level as protective coatings. They also can be used for membrane waterproofing or for bedding and filling the joints of brickwork. Either asphaltic or coal-tar pitch materials of dampproofing and waterproofing grade are used, together with mineral aggregates as coarse as sand.

4.84 BITUMINOUS PAVEMENTS

Asphalts for pavement (ASTM D946) contain petroleum asphalt cement, derived by the distillation of asphaltic petroleum. Various grades are designated as 40–50, 60–70, 85–100, 120–150, and 200–300, depending upon the depth of penetration of a standard needle in a standard test (ASTM D5).

Emulsions range from low to high viscosity and quick- to slow-setting (ASTM D977).

4.85 ASPHALT BIBLIOGRAPHY

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JOINT SEALS

Calking compounds, sealants, and gaskets are employed to seal the points of contact between similar and dissimilar building materials that cannot otherwise be made completely tight. Such points include glazing, the joints between windows and walls, the many joints occurring in the increasing use of panelized construction, the copings of parapets, and similar spots.

The requirements of a good joint seal are: (1) good adhesion to or tight contact with the surrounding materials, (2) good cohesive strength, (3) elasticity to allow for compression and extension as surrounding materials retract or approach each other because of changes in moisture content or temperature, (4) good durability or the ability to maintain their properties over a long-period of time without marked deterioration, and (5) no staining of surrounding materials such as stone.

4.86 CALKING COMPOUNDS

These sealers are used mostly with traditional materials such as masonry, with relatively small windows, and at other points where motion of building components is relatively small. They are typically composed of elastomeric polymers or bodied linseed or soy oil, or both, combined with calcium carbonate (ground marble or limestone), tinting pigments, a gelling agent, drier, and mineral spirits (thinners).

Two types of commonly employed, gun grade and knife grade. Gun grades are viscous semiliquids suitable for application by hand or air-operated calking guns. Knife grades are stiffer and are applied by knife, spatula, or mason's pointing tools.

Because calking compounds are based on drying oils that eventually harden in contact with the air, the best joints are generally thick and deep, with a relatively small portion exposed to the air. The exposed surface is expected to form a tough protective skin for the soft mass underneath, which in turn provides the cohesiveness, adhesiveness, and elasticity required. Thin shallow beads cannot be expected to have the durability of thick joints with small exposed surface areas.

4.87 SEALANTS

For joints and other points where large movements of building components are expected, elastomeric materials may be used as sealants. Whereas traditional calking compounds should not be used where movements of more than 5% of joint width or at most 10% are expected, larger movements, typically 10 to 25%, can be accommodated by the rubbery sealants.

Some elastomeric sealants consist of two components, mixed just before application. Polymerization occurs, leading to conversion of the viscous material to a rubbery consistency. The working time or pot life before this occurs varies, depending upon formulation and temperature, from a fraction of an hour to several hours or a day. Other formulations are single-component and require no mixing. They harden upon exposure to moisture in the air.

Various curing agents, accelerators, plasticizers, fillers, thickeners, and other agents may be added, depending on the basic material and the end-use requirements.

Among the polymeric materials employed are:

Acrylics: solvent-release type, water-release type, latex

Butyls: skinning and nonskinning

Polysulfide: two-part and one-part

Silicone: one-part

Polyurethane: two-part and one-part

Chlorosulfonated polyethylene: one-part

Polyurethane-polyepoxide: two-part

Characteristics of the preceding formulations vary. Hence, the proper choice of materials depends upon the application. A sealant with the appropriate hardness, extensibility, useful temperature ranges, expected life, dirt pickup, staining, colorability, rate of cure to tack-free condition, toxicity, resistance to ultraviolet light, and other attributes should be chosen for the specific end use.

In many joints, such as those between building panels, it is necessary to provide backup; that is, a foundation against which the compound can be applied. This serves to limit the thickness of the joint, to provide the proper ratio of thickness to width, and to force the compound into intimate contact with the substrate, thereby promoting adhesion. For the purpose, any of various compressible materials, such as polyethylene or polyurethane rope, or oakum, may be employed.

To promote adhesion to the substrate, various primers may be needed. (To prevent adhesion of the compound to parts of the substrate where adhesion is not wanted, any of various liquid and tape bond-breakers may be employed.) Generally, good adhesion requires dry, clean surfaces free of grease and other deleterious materials.

4.88 GASKETS

Joint seals described in Arts. 4.86 and 4.87 are formed in place; that is, soft masses are put into the joints and conform to their geometry. A gasket, on the other hand, is preformed and placed into a joint whose geometry must conform with the gasket in such a way as to seal the joint by compression of the gasket. Gaskets, however, are cured under shop-controlled conditions, whereas sealants cure under variable and not always favorable field conditions.

Rubbery materials most commonly employed for gaskets are cellular or noncellular (dense) neoprene, EPDM (ethylene-propylene polymers and terpolymers), and polyvinylchloride polymers.

Gaskets are generally compression types or lock-strip (*zipper*) types. The former are forced into the joint and remain tight by being kept under compression. With lock-strip gaskets, a groove in the gasket permits a lip to be opened and admit glass or other panel, after which a strip is forced into the groove, tightening the gasket in place. If the strip is separable from the gasket, its composition is often harder than the gasket itself.

For setting large sheets of glass and similar units, setting or supporting spacer blocks of rubber are often combined with gaskets of materials such as vulcanized synthetic rubber and are finally sealed with the elastomeric rubber-based sealants or glazing compounds.

4.89 JOINT SEALS BIBLIOGRAPHY

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PAINTS AND OTHER COATINGS

Protective and decorative coatings generally employed in building are the following:

Oil Paint. Drying-oil vehicles or binders plus opaque and extender pigments.

Water Paint. Pigments plus vehicles based on water, casein, protein, oil emulsions, and rubber or resin latexes, separately or in combination.

Calcimine. Water and glue, with or without casein, plus powdered calcium carbonate and any desired colored pigments.

Varnish. Transparent combination of drying oil and natural or synthetic resins.

Enamel. Varnish vehicle plus pigments.

Lacquer. Synthetic-resin film former, usually nitrocellulose, plus plasticizers, volatile solvents, and other resins.

Shellac. Exudations of the lac insect, dissolved in alcohol.

Japan. Solutions of metallic salts in drying oils, or varnishes containing asphalt and opaque pigments.

Aluminum Paint. Fine metallic aluminum flakes suspended in drying oil plus resin, or in nitrocellulose.

4.90 VEHICLES OR BINDERS

Following are descriptions of the most commonly used vehicles and binders for paint:

Natural Drying Oils. Drying oils harden by absorbing oxygen. The most important natural oils are linseed from flax seed (for many years the standard paint vehicle), tung oil (faster drying, good compatibility with varnish), oiticica oil (similar to tung), safflower (best nonyellowing oil), soybean (flexible films), dehydrated caster (good adhesion, fast drying), and fish oil (considered inferior but cheap).

Alkyds. These, the most widely used paint vehicles, are synthetic resins that are modified with various vegetable oils to produce clear resins that are harder than natural oils. Properties of the film depend on relative proportions of oil and resin. The film is both air drying and heat hardening.

Latexes. Latex paints are based on emulsions of various polymers including acrylics, polyvinyl acetate, styrene-butadiene, polyvinyl chloride, and rubber. They are easy to apply, dry quickly, have no solvent odor, and application tools are easily cleaned with soap and water. The films adhere well to various surfaces, have good color retention, and have varying degrees of flexibility.

Epoxy and Epoxy-Polyester. Catalyzed two-part, all-epoxy coatings are formed by addition of a catalyst to the liquid epoxy just before application (pot life a few minutes to a day). Films are as hard as many baked-on coatings and are resistant to solvents and traffic. Oil-modified epoxy esters, in contrast, harden on oxidation without a catalyst. They are less hard and chemically resistant than catalyzed epoxies, but dry fast and are easily applied. Epoxy-polyesters mixed just before use produce smooth finishes suitable for many interior surfaces and are chemically resistant.

Polyurethanes. These produce especially abrasion-treatment, fast-hardening coatings. Two-component formulations, of variable pot life, are mixed just before use. One-component formulations cure by evaporation and reaction with moisture in air (30 to 90% relative humidity). Oils and alkyds may be added.

Vinyl Solutions. Solutions of polyvinyl chloride and vinyl esters dry rapidly and are built up by successive, sprayed thin coatings. They characteristically have low gloss, high flexibility, and inertness to water but are sensitive to some solvents. Adhesion may be a problem. Weather resistance is excellent.

Dryers. These are catalysts that hasten the hardening of drying oils. Most dryers are salts of heavy metals, especially cobalt, manganese, and lead, to which salts of zinc and calcium may be added. Iron salts, usable only in dark coatings, accelerate hardening at high temperatures. Dryers are normally added to paints to hasten hardening, but they must not be used too liberally or they cause rapid deterioration of the oil by overoxidation.

Thinners. These are volatile constituents added to coatings to promote their spreading qualities by reducing viscosity. They should not react with the other constituents and should evaporate completely. Commonly used thinners are turpentine and mineral spirits, i.e., derivatives of petroleum and coal tar.

4.91 PIGMENTS FOR PAINTS

Pigments may be classified as white and colored, or as opaque and extender pigments. The hiding power of pigments depends on the difference in index of refraction of the pigment and the surrounding medium—usually the vehicle of a protective coating. In opaque pigments, these indexes are markedly different from those of the vehicles (oil or other); in extender pigments, they are nearly the same. The comparative hiding efficiencies of various pigments must be evaluated on the basis of hiding power per pound and cost per pound.

Principal white pigments, in descending order of relative hiding power per pound, are approximately as follows: rutile titanium dioxide, anatase titanium dioxide, zinc sulfide, titanium-calcium, titanium-barium, zinc sulfide-barium, titanated lithopone, lithopone, antimony oxide, zinc oxide.

Zinc oxide is widely used by itself or in combination with other pigments. Its color is unaffected by many industrial and chemical atmospheres. It imparts gloss and reduces chalking but tends to crack and alligator instead.

Zinc sulfide is a highly opaque pigment widely used in combination with other pigments.

Titanium dioxide and extended titanium pigments have high opacity and generally excellent properties. Various forms of the pigments have different properties. For example, anatase titanium dioxide promotes chalking, whereas rutile inhibits it.

Colored pigments for building use are largely inorganic materials, especially for outdoor use, where the brilliant but fugitive organic pigments soon fade. The principal inorganic colored pigments are:

Metallic. Aluminum flake or ground particle, copper bronze, gold leaf, zinc dust

Black. Carbon black, lampblack, graphite, vegetable black, and animal blacks

Earth colors. Yellow ocher, raw and burnt umber, raw and burnt sienna; reds and maroons

Blue. Ultramarine, iron ferrocyanide (Prussian, Chinese, Milori)

Brown. Mixed ferrous and ferric oxide

Green. Chromium oxide, hydrated chromium oxide, chrome greens

Orange. Molybdated chrome orange

Red. Iron oxide, cadmium red, vermilion

Yellow. Zinc chromate, cadmium yellows, hydrated iron oxide

Extender pigments are added to extend the opaque pigments, increase durability, provide better spreading characteristics, and reduce cost. The principal extender pigments are silica, china clay, talc, mica, barium sulfate, calcium sulfate, calcium carbonate, and such materials as magnesium oxide, magnesium carbonate, barium carbonate, and others used for specific purposes.

4.92 RESINS FOR PAINTS

Natural and synthetic resins are used in a large variety of air-drying and baked finishes. The natural resins include both fossil resins, which are harder and usually superior in quality, and recent resins tapped from a variety of resin-exuding trees. The most important fossil resins are amber (semiprecious jewelry), Kauri, Congo, Boea Manila, and Pontianak. Recent resins include Damar, East India, Batu, Manila, and rosin. Shellac, the product of the lac insect, may be considered to be in this class of resins.

The synthetic resins, in addition to the ones discussed in Art. 4.90, are used for applications requiring maximum durability. Among them are phenol formaldehyde, melamine formaldehyde, urea formaldehyde, silicones, fluorocarbons, and cellulose acetate-butyrate.

Phenolics in varnishes are used for outdoor and other severe applications on wood and metals. They are especially durable when baked.

Melamine and urea find their way into a large variety of industrial finishes, such as automobile and refrigerator finishes.

Silicones are used when higher temperatures are encountered that can be borne by the other finishes.

Fluorocarbons are costly but provide high-performance coatings, industrial siding, and curtain walls with excellent gloss retention, stain resistance, and weather resistance. Cellulose acetate-butyrate provides shop-applied, high-gloss finishes.

4.93 COATINGS BIBLIOGRAPHY

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