13

CONCRETE CONSTRUCTION

A physical sciences center at Dartmouth College, built in a highly irregular space bounded by three existing buildings, typifies the potential of reinforced concrete to make expressive, highly individual buildings. *(Architects: Shepley Bulfinch Richardson and Abbott. Photograph: Ezra Stoller © ESTO)*

Concrete is the universal material of construction. According to the World Business Council for Sustainable Development, concrete is, after water, the most widely used material on earth. The raw ingredients for its manufacture are readily available in almost every part of the globe, and concrete can be made into buildings with tools ranging from a primitive shovel to a computerized precasting plant. Concrete does not rot or burn; it is relatively low in cost; and it can be used for every building purpose, from lowly pavings to sturdy structural frames to handsome exterior claddings and interior finishes.

But concrete is the only major structural material commonly manufactured on site, it has no form of its own, and it has no useful tensile strength. Before its limitless architectural potential can be realized, the designer and builder must learn to produce concrete of consistent and satisfactory quality, to combine concrete skillfully with steel reinforcing to bring out the best structural characteristics of each material, and to mold and shape it to forms appropriate to its qualities and to our building needs.

HISTORY

The ancient Romans, while quarrying limestone for mortar, accidentally discovered a silica- and alumina-bearing mineral on the slopes of Mount Vesuvius that, when mixed with limestone and burned, produced a cement that exhibited a unique property: When mixed with water and sand, it produced a mortar that could harden underwater as well as in the air. In fact, it was stronger when it hardened underwater. This mortar was also harder, stronger, much more adhesive, and cured much more quickly than the ordinary lime mortar to which they were accustomed. In time, it not only became the preferred mortar for use in all their building projects, but it also began to alter the character of Roman construction. Masonry of stone or brick came to be used to build only the surface layers of piers, walls, and vaults, and the hollow interiors were filled entirely with large volumes of the new type of mortar (Figure 13.2). We now know that this mortar contained all the essential ingredients of modern portland cement and that the Romans were the inventors of concrete construction.

Knowledge of concrete construction was lost with the fall of the Roman Empire, not to be regained until the latter part of the 18th century, when a number of English inventors began experimenting with both natural and artificially produced cements. Joseph Aspdin, in 1824, patented an artificial cement that he named *portland cement,* after English Portland limestone, whose durability as a building stone was legendary. His cement was soon in great demand, and the name Portland remains in use today.

Reinforced concrete, in which steel bars are embedded to resist tensile forces, was developed in the 1850s by several people simultaneously. Among them were the Frenchman J. L. Lambot, who built several reinforced concrete boats in Paris in 1854, and an American, Thaddeus Hyatt, who made and tested a number of reinforced concrete beams. But the combination of steel and concrete did not come into widespread use until a

FIGURE 13.1
At the time concrete is placed, it has no form of its own. This bucket of fresh concrete was filled on the ground by a transit-mix truck and hoisted to the top of the building by a crane. The worker at the right has opened the valve in the bottom of the bucket to discharge the concrete into the formwork. *(Reprinted with permission of the Portland Cement Association from* Design and Control of Concrete Mixtures, *12th edition; Photos: Portland Cement Association, Skokie, IL)*

French gardener, Joseph Monier, obtained a patent for reinforced concrete flower pots in 1867 and went on to build concrete water tanks and bridges of the new material. By the end of the 19th century, engineering design methods had been developed for structures of reinforced concrete and a number of major structures had been built. By this time, the earliest experiments in prestressing (placing the reinforcing steel under tension before the structure supports a load) had also been carried out, although it remained for Eugene Freyssinet in the 1920s to establish a scientific basis for the design of prestressed concrete structures.

CEMENT AND CONCRETE

Concrete is a rocklike material produced by mixing coarse and fine *aggregates*, portland cement, and water and allowing the mixture to harden. *Coarse aggregate* is normally gravel or crushed stone, and *fine aggregate* is sand. Portland cement, hereafter referred to simply as cement, is a fine gray powder. During the hardening, or *curing*, of concrete, the cement combines chemically with water to form strong crystals that bind the aggregates together, a process called *hydration*. During this process, considerable heat, called *heat of hydration*, is given off, and, especially as excess water evaporates from the concrete, the concrete shrinks slightly, a phenomenon referred to as *drying shrinkage*. The curing process does not end abruptly unless it is artificially interrupted. Rather, it tapers off gradually over long periods of time, though, for practical purposes, concrete is normally considered fully cured after 28 days.

In properly formulated concrete, the majority of the volume consists of coarse and fine aggregate, proportioned and graded so that the fine particles completely fill the spaces between the coarse ones (Figure 13.3). Each particle is completely coated with a paste of cement and water that bonds it fully to the surrounding particles.

FIGURE 13.2
Hadrian's Villa, a large palace built near Rome between A.D. 125 and 135, used unreinforced concrete extensively for structures such as this dome. *(Photo by Edward Allen)*

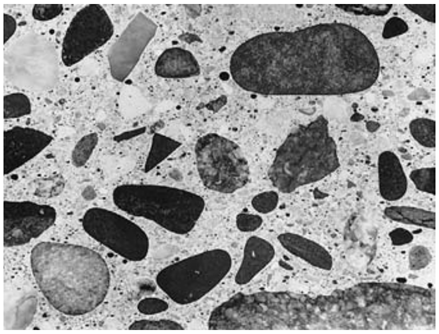


FIGURE 13.3
Photograph of a polished cross section of hardened concrete, showing the close packing of coarse and fine aggregates and the complete coating of every particle with cement paste. *(Reprinted with permission of the Portland Cement Association from* Design and Control of Concrete Mixtures, *12th edition; Photos: Portland Cement Association, Skokie, IL)*

Cement

Portland cement may be manufactured from any of a number of raw materials, provided that they are combined to yield the necessary amounts of lime, iron, silica, and alumina. Lime is commonly furnished by limestone, marble, marl, or seashells. Iron, silica, and alumina may be provided by clay or shale. The exact ingredients depend on what is readily available, and the recipe varies widely from one geographic region to another, often including slag or flue dust from iron furnaces, chalk, sand, ore washings, bauxite, and other minerals. To make portland cement, the selected constituents are crushed, ground, proportioned, and blended. Then they are conducted through a long, rotating kiln at temperatures of 2600 to 3000 degrees Fahrenheit (1400 1650°C) to produce *clinker* (Figures 13.4 and 13.5). After cooling, the clinker is pulverized to a powder finer than flour. Usually at this stage a small amount of gypsum is added to act as a retardant during the eventual concrete curing process. This finished powder, portland cement, is either packaged in bags or shipped in bulk. In the United States, a standard bag of cement contains 1 cubic foot (0.09 m^2) of volume and weighs 94 pounds (43 kg).

The quality of portland cement is established by ASTM C150, which identifies eight different types:

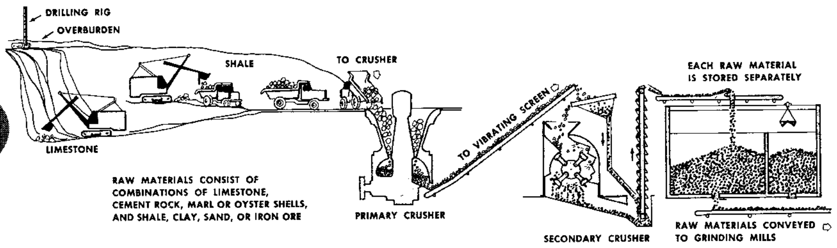
Type I	Normal
Type IA	Normal, air entraining
Type II	Moderate resistance to sulfate attack
Type IIA	Moderate sulfate resistance, air entraining
Type III	High early strength
Type IIIA	High early strength, air entraining
Type IV	Low heat of hydration
Type V	High resistance to sulfate attack

Type I cement is used for most purposes in construction. Types II

STEPS IN THE MANUFACTURE OF PORTLAND CEMENT

STONE IS FIRST REDUCED TO 5-IN. SIZE, THEN 3/4-IN., AND STORED

1



BURNING CHANGES RAW MIX CHEMICALLY INTO CEMENT CLINKER

3

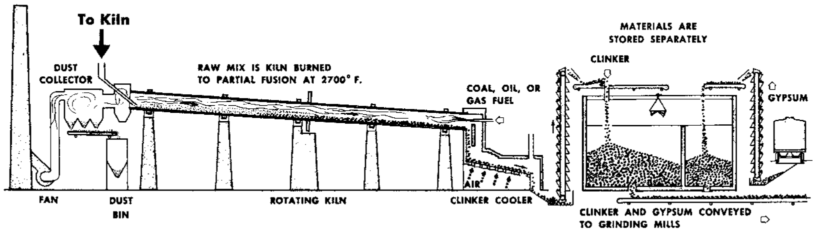


FIGURE 13.4
A rotary kiln manufacturing cement clinker. *(Reprinted with permission of the Portland Cement Association from* Design and Control of Concrete Mixtures, *12th edition; Photos: Portland Cement Association, Skokie, IL)*

FIGURE 13.6
A photomicrograph of a small section of air-entrained concrete shows the bubbles of entrained air (0.01 inch equals 0.25 mm). *(Reprinted with permission of the Portland Cement Association from* Design and Control of Concrete Mixtures, *12th edition; Photos: Portland Cement Association, Skokie, IL)*

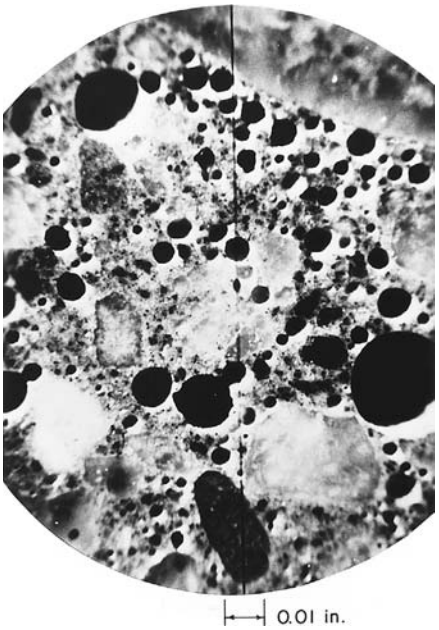
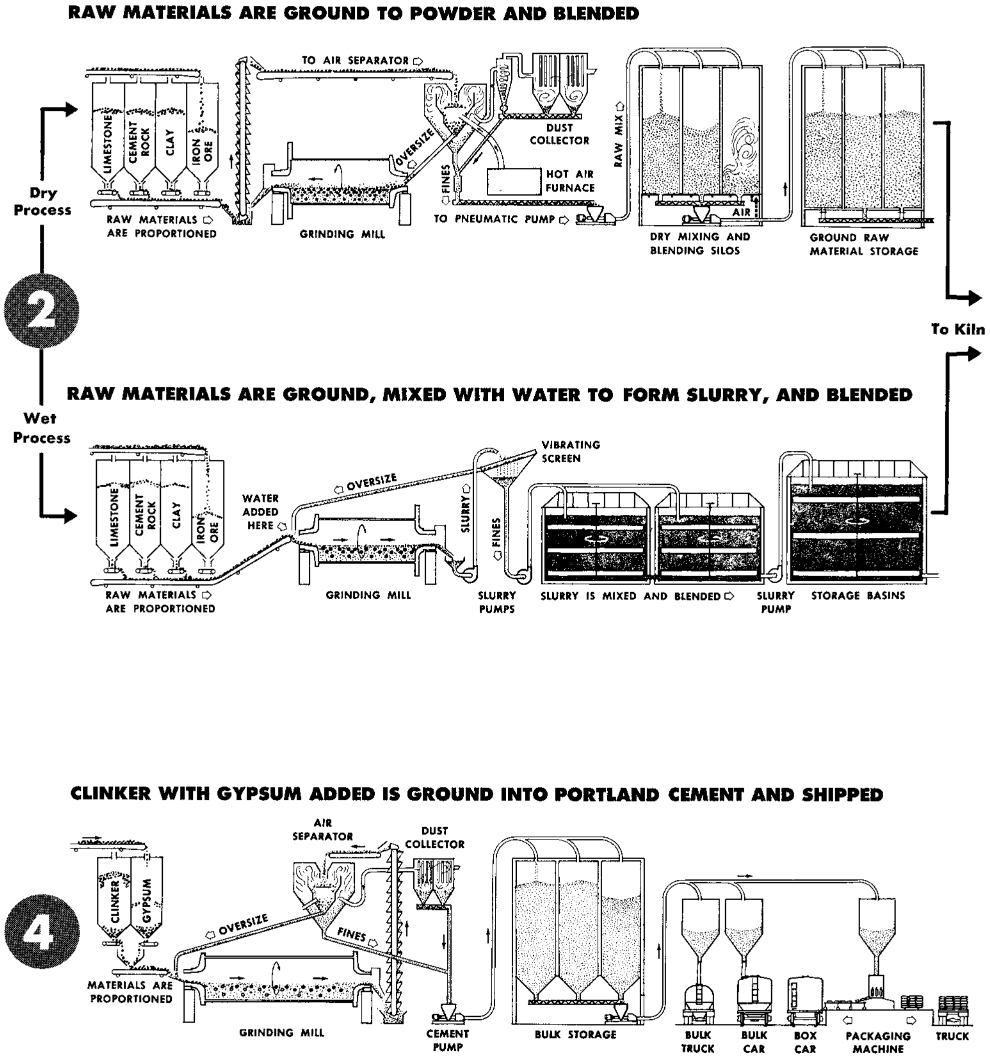


FIGURE 13.5
Steps in the manufacture of portland cement. *(Reprinted with permission of the Portland Cement Association from* Design and Control of Concrete Mixtures, *12th edition; Photos: Portland Cement Association, Skokie, IL)*



and V are used where the concrete will be in contact with water that has a high concentration of sulfates. Type III hardens more quickly than the other types and is employed in situations where a reduced curing period is desired (as may be the case in cold weather), in the precasting of concrete structural elements, or when the construction schedule must be accelerated. Type IV is used in massive structures such as dams, where the heat emitted by curing concrete may raise the temperature of the concrete to damaging levels.

Recent changes to the ASTM C150 standard allow the inclusion of ground limestone in portland cement (as an additive in the finished cement, distinct from its use as a raw ingredient in the manufacture of clinker). This will provide economic and environmental benefits, reducing consumption of raw materials and energy as well as lessening emissions of carbon dioxide and cement kiln dust.

Air-entraining cements contain ingredients that cause microscopic air bubbles to form in the concrete during mixing (Figure 13.6). These bubbles, which usually comprise 2 to 8 percent

CONSIDERATIONS OF SUSTAINABILITY IN CONCRETE CONSTRUCTION

Worldwide each year, the making of concrete consumes 1.6 billion tons (1.5 billion metric tons) of portland cement, 10 billion tons (9 billion metric tons) of sand and rock, and 1 billion tons (0.9 billion metric tons) of water, making the concrete industry the largest user of natural resources in the world.

The quarrying of the raw materials for concrete in open pits can result in soil erosion, pollutant runoff, habitat loss, and ugly scars on the landscape.

Concrete construction also uses large quantities of other materials—wood, wood panel products, steel, aluminum, plastics—for formwork and reinforcing.

The total energy embodied in a pound of concrete varies, especially with the design strength. This is because higher-strength concrete relies on a greater proportion of portland cement in its mix, and the energy required to produce portland cement is very high in comparison to concrete's other ingredients. For average-strength concrete, the embodied energy ranges from about 200 to 300 BTU per pound (0.5-0.7 MJ/kg).

There are various useful approaches to increasing the sustainability of concrete construction:

- Use waste materials from other industries, such as fly ash from power plants, slag from iron furnaces, copper slag, foundry sand, mill scale, sandblasting grit, and others, as components of cement and concrete.
- Use concrete made from locally extracted materials and local processing plants to reduce the transportation of construction materials over long distances.
- Minimize the use of materials for formwork and reinforcing.
- Reduce energy consumption, waste, and pollutant emissions from every step of the process of concrete construction, from quarrying of raw materials through the eventual demolition of a concrete building.
- In regions where the quality of the construction materials is low, improve the quality of concrete so that concrete buildings will last longer, thus reducing the demand for concrete and the need to dispose of demolition waste.

Portland Cement

The production of portland cement is by far the largest user of energy in the concrete construction process, accounting for about 85 percent of the total energy required. Portland cement production also accounts for roughly 5 percent of all carbon dioxide gas generated by human activities worldwide and about 1.5 percent of such emissions in North America.

Since 1970, the North American cement industry has reduced the amount of energy expended in cement production by one-third, and the industry continues to work toward further reductions.

The manufacture of cement produces large amounts of air pollutants and dust. For every ton of cement clinker produced, almost a ton of carbon dioxide, a greenhouse gas, is released into the atmosphere. Cement production accounts for approximately 1.5 percent of carbon dioxide emissions in the United States and 5 percent of carbon dioxide emissions worldwide.

In the past 35 years, the emission of particulates from cement production has been reduced by more than 90 percent.

The cement industry is committed to reducing greenhouse gas emissions per ton of product by 10 percent from 1990 levels by the year 2020. According to the Portland Cement Association, over concrete's lifetime, it reabsorbs roughly half of the carbon dioxide released during the original cement manufacturing process.

The amount of portland cement used as an ingredient in concrete, and as a consequence, the energy required to produce the concrete, can be substantially reduced by the addition of certain industrial waste materials with cementing properties to the concrete mix. Substituting such supplementary cementitious materials, including fly ash, silica fume, and blast furnace slag, for up to half the portland cement in the concrete, can result in reductions in embodied energy of as great as one-third.

When added to concrete, fly ash is most commonly substituted for portland cement at rates of between 15 and 25 percent. Mixes with even higher replacement rates, called *high-volume-fly-ash (HVFA) concrete*, are also finding increased acceptance. Concrete mixed with fly ash as an ingredient gains other benefits as well: It needs less water than normal concrete, its heat of hydration is lower, and it shrinks less, all characteristics that lead to a denser, more durable product. Research is underway to develop concrete mixes in which fly ash completely replaces all portland cement.

Waste materials from other industries can also be used as cementing agents—wood ash and rice-husk ash are two examples. Used motor oil and used rubber vehicle tires can be employed as fuel in cement kilns. And while consuming waste products from other industries, a cement manufacturing plant can, if efficiently operated, generate virtually no solid waste itself.

Aggregates and Water

Sand and crushed stone come from abundant sources in many parts of the world, but high-quality aggregates are becoming scarce in some countries.

In rare instances, aggregate in concrete has been found to be a source of radon gas. Concrete itself is not associated with indoor air quality problems.

Waste materials such as crushed, recycled glass, used foundry sand, and crushed, recycled concrete can substitute for a portion of the conventional aggregates in concrete.

Water of a quality suitable for concrete is scarce in many developing countries. Concretes that use less water by using superplasticizers, air entrainment, and fly ash could be helpful.

Wastes

A significant percentage of fresh concrete is not used because the truck that delivers it to the building site contains more than is needed for the job. This concrete is often dumped on the site, where it hardens and is later removed and taken to a landfill for disposal. An empty transit-mix truck must be washed out after transporting each batch, which produces a substantial volume of water that contains portland cement particles, admixtures, and aggregates. These wastes can be recovered and recycled as aggregates and mixing water, but more concrete suppliers need to implement schemes for doing this.

Formwork

Formwork components that can be reused many times have a clear advantage over single-use forms, which represent a large waste of construction material.

Form release compounds and curing compounds should be chosen for low volatile organic compound content and biodegradability.

Insulating concrete forms eliminate most temporary formwork and produce concrete walls with high thermal insulating values.

Reinforcing

In North America, reinforcing bars are made almost entirely from recycled steel scrap, primarily junked automobiles. This reduces resource depletion and energy consumption significantly.

Demolition and Recycling

When a concrete building is demolished, its reinforcing steel can be recycled.

In many if not most cases, fragments of demolished concrete can be crushed, sorted, and used as aggregates for new concrete. At present, however, most demolished concrete is buried on the site, used to fill other sites, or dumped in a landfill.

Green Uses of Concrete

Pervious concrete, made with coarse aggregate only, can be used to make porous pavings that allow stormwater to filter into the ground, helping to recharge aquifers and reduce stormwater runoff.

Concrete is a durable material that can be used to construct buildings that are long-lasting and suitable for adaptation and reuse, thereby reducing the environmental impacts of building demolition and new construction.

In brownfield development, concrete fill materials can be used to stabilize soils and reduce leachate concentrations.

Where structured parking garages (often constructed of concrete) replace surface parking, open space is preserved.

Concrete's thermal mass can be exploited to reduce building heating and cooling costs by storing excess heat during overheated periods of the day or week and releasing it back to the interior of the building during underheated periods.

Lighter-colored concrete paving reflects more solar radiation than darker asphalt paving, leading to lower paving surface temperatures and reduced urban heat island effects.

Interior concrete slabs made with white concrete can improve illumination, visibility, and worker safety within interior spaces without the expense or added energy consumption of extra light fixtures or increasing the light output from existing fixtures. White concrete is made with white cement and white aggregates.

Photocatalytic agents can be added to concrete used in the construction of roads and buildings. In the presence of sunlight, the concrete chemically breaks down carbon monoxide, nitrogen oxide, benzene, and other air pollutants.

of the volume of the finished concrete, improve workability during placement of the concrete and, more importantly, greatly increase the resistance of the cured concrete to damage caused by repeated cycles of freezing and thawing. Air-entrained concrete is commonly used for pavings and exposed architectural concrete in cold climates. With appropriate adjustments in the formulation of the mix, air-entrained concrete can achieve the same structural strength as normal concrete.

White portland cement is produced by controlling the quantities of certain minerals, such as oxides of iron and manganese, found in the ingredients of cement, that contribute to cement's usual gray color. White portland cement is used for architectural applications to produce concrete that is lighter and more uniform in color or, when combined with other coloring agents, to enhance the appearance of integrally colored concrete.

Aggregates and Water

Because aggregates make up roughly three-quarters of the volume of concrete, the structural strength of a concrete is heavily dependent on the quality of its aggregates. Aggregates for concrete must be strong, clean, resistant to freeze-thaw deterioration, chemically stable, and properly graded for size distribution. An aggregate that is dusty or muddy will contaminate the cement paste with inert particles that weaken it, and an aggregate that contains any of a number of chemicals from sea salt to organic compounds can cause problems ranging from corrosion of reinforcing steel to retardation of the curing process and ultimate weakening of the concrete. A number of standard ASTM laboratory tests are used to assess the various qualities of aggregates.

Size distribution of aggregate particles is important because a range of sizes must be included and properly proportioned in each concrete mix to achieve close packing of the particles. A concrete aggregate is graded for size by passing a sample of it through a standard assortment of sieves with diminishing mesh spacings, then weighing the percentage of material that passes through each sieve. This test makes it possible to compare the particle size distribution of an actual aggregate with that of an ideal aggregate. Size of aggregate is also significant because the largest particle in a concrete mix must be small enough to pass easily between the most closely spaced reinforcing bars and to fit easily into the formwork. In general, the maximum aggregate size should not be greater than three-fourths of the clear spacing between bars or one-third the depth of a slab. For very thin slabs and toppings, a ⅜-inch (9-mm) maximum aggregate diameter is often specified. A ¾-inch or 1½-inch (19-mm or 38-mm) maximum size is common for much slab and structural work, but aggregate diameters up to 6 inches (150 mm) are used in dams and other massive structures. Producers of concrete aggregates sort their product for size using a graduated set of screens and can furnish aggregates graded to order.

Lightweight aggregates are used instead of sand and crushed stone for various special types of concrete. *Structural lightweight aggregates* are made from minerals such as shale. The shale is crushed to the desired particle sizes, then heated in an oven to a temperature at which the shale becomes plastic in consistency. The small amount of water that occurs naturally in the shale turns to steam and pops the softened particles like popcorn. Concrete made from this *expanded shale aggregate* has a density about 20 percent less than that of normal concrete, yet it is nearly as strong. Nonstructural lightweight concretes are made for use in insulating roof toppings that have densities only one-fourth to one-sixth that of normal concrete. The aggregates in these concretes are usually expanded mica (*vermiculite*) or expanded volcanic glass (*perlite*), both produced by processes much like that used to make expanded shale. However, both of these aggregates are much less dense than expanded shale, and the density of the concretes in which they are used is further reduced by admixtures that entrain large amounts of air during mixing.

Figure 13.7
Taking a sample of coarse aggregate from a crusher yard for testing.
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ASTM standard C1602 defines the requirements for mixing water for concrete. Generally, water must be free of harmful substances, especially organic material, clay, and salts such as chlorides and sulfates. Water that is suitable for drinking has traditionally been considered suitable for making concrete.

Supplementary Cementitious Materials

Various mineral products, called *supplementary cementitious materials (SCMs),* may be added to concrete mixtures as a substitute for some portion of the portland cement to achieve a range of benefits. Supplementary cementitious materials are classified as either pozzolans or hydraulic cements.

Pozzolans are materials that react with the calcium hydroxide in wet concrete to form cementing compounds. They include:

Fly ash, a fine powder that is a waste product from coal-fired power plants, increases concrete strength, decreases permeability, increases sulfate resistance, reduces temperature rise during curing, reduces mixing water, and improves pumpability and workability of concrete. Fly ash also reduces concrete drying shrinkage.

Silica fume, also known as *microsilica,* is a powder that is approximately 100 times finer than portland cement, consisting mostly of silicon dioxide. It is a byproduct of electronic semiconductor chip manufacturing. When added to a concrete mix, it produces extremely high-strength concrete that also has very low permeability.

Natural pozzolans, mostly derived from shales or clays, are used for purposes such as reducing the internal temperature of curing concrete, reducing the reactivity of concrete with aggregates containing sulfates, or improving the workability of concrete. *High reactivity metakaolin* is a unique white-colored natural pozzolan that enhances the brilliance of white or colored concrete while also improving the material's workability, strength, and density. These characteristics make it especially well suited as an ingredient in exposed architectural concrete applications where appearance and finish quality are critical.

Blast furnace slag (also called *slag cement*), a byproduct of iron manufacture, is a *hydraulic cement,* meaning that, like portland cement, it reacts directly with water to form a cementitious compound. It may be added to concrete mixes to improve workability, increase strength, reduce permeability, reduce temperature rise during curing, and improve sulfate resistance.

Supplementary cementitious materials may be added to portland cement during the cement manufacturing process, in which case the resulting product is called a *blended cement,* or they may be added to the concrete mix at the batch plant. The use of supplementary cementitious materials also enhances the sustainability of concrete by reducing reliance on more energy-intensive portland cement and, in many cases, by making productive use of waste products from other industrial manufacturing processes. Half or more of the concrete produced in North America includes some supplementary cementitious materials in its mix.

Admixtures

Ingredients other than cement and other cementitious materials, aggregates, and water, broadly referred to as *admixtures,* are often added to concrete to alter its properties in various ways:

Air-entraining admixtures increase the workability of the wet concrete, reduce freeze-thaw damage, and, when used in larger amounts, create very lightweight nonstructural concretes with thermal insulating properties.

Water-reducing admixtures allow a reduction in the amount of mixing water while retaining the same workability, which results in a higher-strength concrete.

High-range water-reducing admixtures, also known as *superplasticizers,* are organic compounds that transform a stiff concrete mix into one that flows freely into the forms. They are used either to facilitate placement of concrete under difficult circumstances or to reduce the water content of a concrete mix in order to increase its strength.

Accelerating admixtures cause concrete to cure more rapidly, and *retarding admixtures* slow its curing to allow more time for working with the wet concrete.

Workability agents improve the plasticity of wet concrete to make it easier to place in forms and finish. They include pozzolans and air-entraining admixtures, along with certain fly ashes and organic compounds.

Shrinkage-reducing admixtures reduce drying shrinkage and the cracking that results.

Corrosion inhibitors are used to reduce rusting of reinforcing steel in structures that are exposed to road deicing salts or other corrosion-causing chemicals.

Freeze protection admixtures allow concrete to cure satisfactorily at temperatures as low as 20 degrees Fahrenheit (7°C).

Extended set-control admixtures may be used to delay the curing reaction in concrete for any period up to several days. They include two components: The stabilizer component, added at the time of initial mixing, defers the onset of curing indefinitely; the activator component, added when desired, reinitiates the curing process.

Coloring agents are dyes and pigments used to alter and control the color of concrete for building components whose appearance is important.

MAKING AND PLACING CONCRETE

The quality of cured concrete is measured by any of several criteria, depending on its end use. For structural columns, beams, and slabs, compressive strength and stiffness are important. For pavings and floor slabs, flatness, surface smoothness, and abrasion resistance are also important. For pavings and exterior concrete walls, a high degree of weather resistance is required. Watertightness is important in concrete tanks, dams, and walls. Regardless of the criterion to which one is working, however, the rules for making high-quality concrete are much the same: Use clean, sound ingredients; mix them in the correct proportions; handle the wet concrete properly to avoid segregating its ingredients; and cure the concrete carefully under controlled conditions.

Proportioning Concrete Mixes

The design of concrete mixtures is a science that can be described here only in its broad outlines. The starting point of any mix design is to establish the desired workability characteristics of the wet concrete, the desired physical properties of the cured concrete, and the acceptable cost of the concrete, keeping in mind that there is no need to spend money to make concrete better than it needs to be for a given application. Concretes with ultimate compressive strengths as low as 2000 psi (13.8 MPa) are satisfactory for some foundation elements. Concretes with ultimate compressive strengths of 20,000 psi (140 MPa) and more, produced with the aid of silica fume, fly ash, and superplasticizer admixtures, are currently being employed in the columns of some high-rise buildings. Acceptable workability is achievable at any of these strength levels.

Given a proper gradation of satisfactory aggregates, the strength of cured concrete is primarily dependent on the amount of cement in the mix and on the *water–cement (w-c) ratio.* Although water is required as a reactant in the curing of concrete, much more water must be added to a concrete mix than is needed for the hydration of the cement to give the wet concrete the necessary fluidity and plasticity for placing and finishing. The extra water eventually evaporates from the concrete, leaving microscopic voids that reduce the strength and surface qualities of the concrete (Figure 13.8). For common concrete applications, absolute water–cement ratios range from about 0.45 to 0.60 by weight, meaning that the weight of the water in the mix does not exceed 45 to 60 percent of the weight of the portland cement. Relatively high water–cement ratios are often favored by concrete workers because they produce a fluid mixture that is easy to place in the forms, but the resulting concrete is likely to be deficient in strength and surface qualities. Lower water–cement ratios make concrete that is denser and strongr and that shrinks less during curing. But unless air-entraining or water-reducing admixtures are included in a low water–cement ratio mix to improve its workability, the concrete will not flow easily into the forms, it will have large voids, and it will finish poorly. It is important that concrete be formulated with the right quantity of water for each situation, enough to ensure workability but not enough to adversely affect the properties of the cured material.

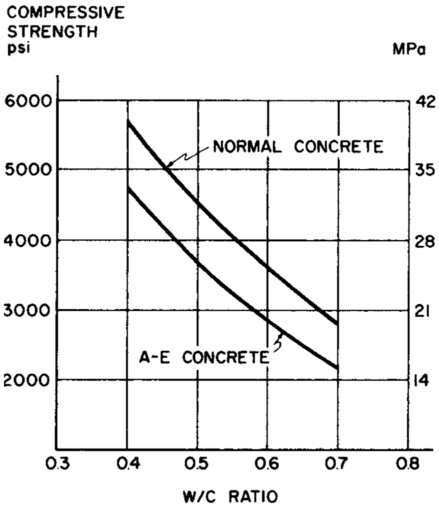


FIGURE 13.8
The effect of the water–cement ratio on the strength of concrete. A-E concrete on the graph refers to air-entrained concrete. *(Reprinted with permission of the Portland Cement Association from* Design and Control of Concrete Mixtures, *12th edition; Photos: Portland Cement Association, Skokie, IL)*

Most concrete in North America is proportioned at central batch plants, using laboratory equipment and engineering knowledge to produce concrete of the proper quality for each project. The concrete is *transit mixed* en route in a rotating drum on the back of a truck so that it is ready to pour by the time it reaches the job site (Figures 13.9 and 13.10). For very small jobs, concrete may be mixed at the job site, either in a small power-driven mixing drum or on a flat surface with shovels. For these small jobs, where the quality of the finished concrete generally does not need to be precisely controlled, proportioning is usually done by rule of thumb. Typically, the dry ingredients are measured volumetrically, using a shovel as a measuring device, in proportions such as one shovel of cement to two of sand to three of gravel, with enough water to make a wet concrete that is neither soupy nor stiff.

Each load of transit-mixed concrete is delivered with a certificate from the batch plant that lists its ingredients and their proportions. As a further check on quality, a *slump test* may be performed at the time of pouring to determine if the desired degree of workability has been achieved without making the concrete too wet (Figures 13.11 and 13.12). For structural concrete, standard test cylinders are also poured from each truckload. Within 48 hours of pouring, the cylinders are taken to a testing laboratory, cured for a specified period under

FIGURE 13.9
Charging a transit-mix truck with measured quantities of cement, aggregates, admixtures, and water at a central batch plant. *(Reprinted with permission of the Portland Cement Association from* Design and Control of Concrete Mixtures, *12th edition; Photos: Portland Cement Association, Skokie, IL)*

FIGURE 13.10
A transit-mix truck discharges its concrete, which was mixed en route in the rotating drum, into a truck-mounted concrete pump, which forces it through a hose to the point in the building at which it is being poured. *(Reprinted with permission of the Portland Cement Association from* Design and Control of Concrete Mixtures, *12th edition; Photos: Portland Cement Association, Skokie, IL)*

standard conditions, and tested for compressive strength (Figure 13.13). If the laboratory results are not up to the required standard, test cores are drilled from the actual members made from the questionable batch of concrete. If the strength of these core samples is also deficient, the contractor may be required to cut out the defective concrete and replace it. Frequently, test cylinders are also cast and cured on the construction site under the same conditions as the concrete in the forms; these may then be tested to determine when the concrete is strong enough to allow removal of forms and temporary supports.

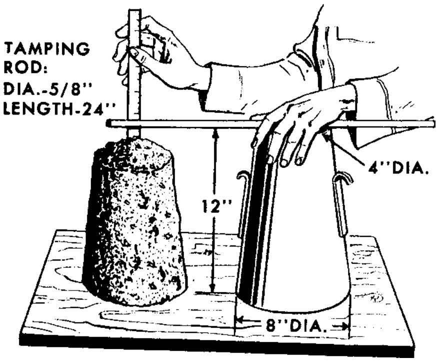


FIGURE 13.11
Illustration of the concrete slump test. The hollow metal cone is filled with concrete and tamped with the rod according to a standard procedure. The cone is carefully lifted off, allowing the wet concrete to sag, or slump, under its own weight. The slump in inches is measured in the manner shown. *(From the U.S. Department of Army, Concrete, Masonry, and Brickwork)*

FIGURE 13.12
Photograph of slump being measured. *(Reprinted with permission of the Portland Cement Association from* Design and Control of Concrete Mixtures, *12th edition; Photos: Portland Cement Association, Skokie, IL)*

Figure 13.13
Inserting a standard concrete test cylinder into a structural testing machine, where it will be crushed to determine its strength. *(Reprinted with permission of the Portland Cement Association from* Design and Control of Concrete Mixtures, *12th edition; Photos: Portland Cement Association, Skokie, IL)*

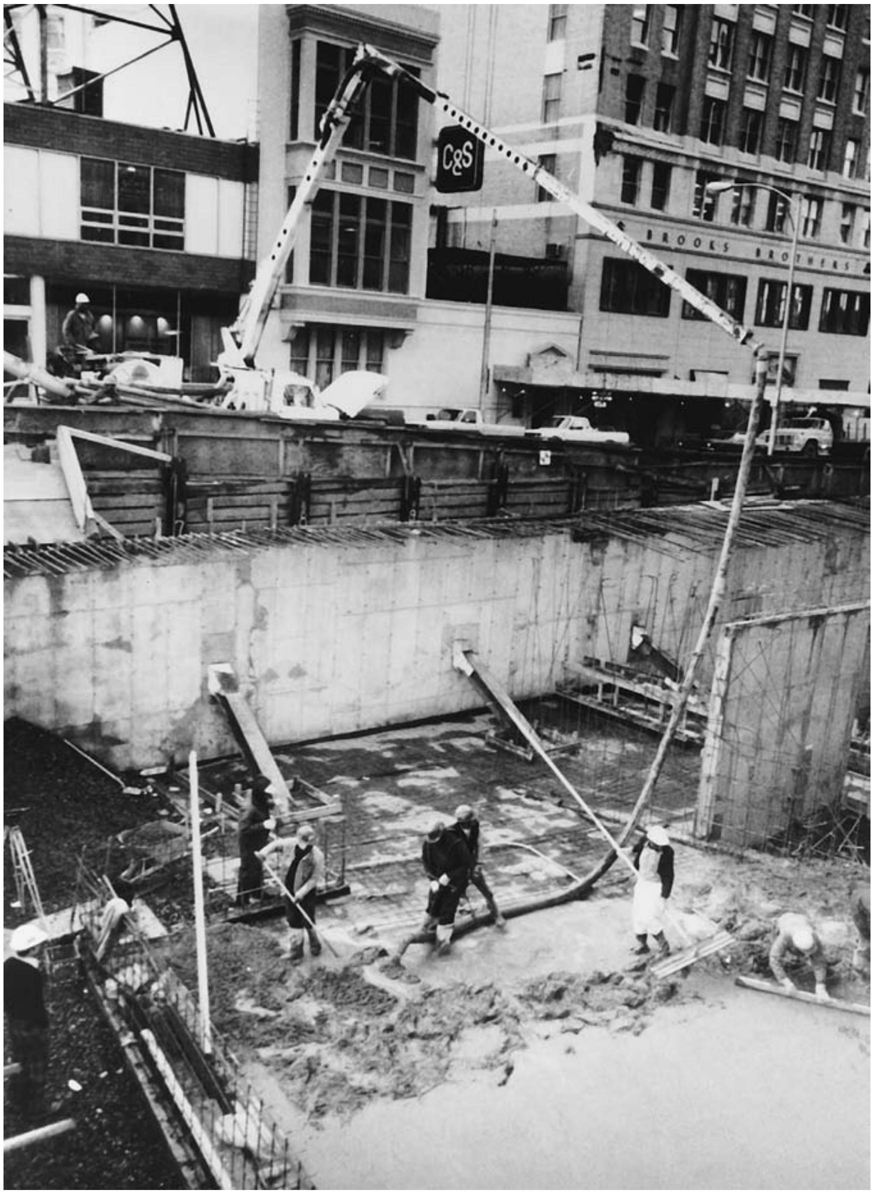


Figure 13.14
Concrete being placed in a basement floor slab with the aid of a concrete pump. Concrete can be pumped for long horizontal distances and many stories into the air. Note also the rather substantial rakers that brace the wall of the excavation. *(Reprinted with permission of the Portland Cement Association from* Design and Control of Concrete Mixtures, *12th edition; Photos: Portland Cement Association, Skokie, IL)*

Handling and Placing Concrete

Freshly mixed concrete is not a liquid but a *slurry*, a semistable mixture of solids suspended in liquid. If it is vibrated excessively, moved horizontally for long distances in the forms, or dropped through constrained spaces, it is likely to *segregate*, which means that the coarse aggregate works its way to the bottom of the form and the water and cement paste rise to the top. The result is concrete of nonuniform and generally unsatisfactory properties. Segregation is prevented by depositing the concrete, fresh from the mixer, as close to its final position as possible. If concrete must be moved a large horizontal distance to reach inaccessible areas of the formwork, it should be pumped through hoses (Figure 13.14) or conveyed in buckets or buggies, rather than pushed across or through the formwork. If concrete must be dropped a distance of more than 3 to 5 feet (1 m or so), care must be taken to ensure that the concrete can fall freely, without obstruction, so that segregation will not occur, or it should be deposited through *dropchutes* that break the fall of the concrete.

Concrete must be *consolidated* in the forms to eliminate trapped air and to fill completely the space around the reinforcing bars and in all corners of the formwork. This may be done by repeatedly thrusting a rod, spade, or immersion-type vibrator into the concrete at closely spaced intervals throughout the formwork. Excessive agitation of the concrete must be avoided, however, or segregation will occur.

Self-consolidating concrete (SCC), a concrete that fills forms completely without requiring vibration or any other method of consolidation, is a more recent development. It is formulated with more fine aggregates than coarse ones, a reversal of the usual proportions, and it includes special superplasticizing admixtures based on polycarboxylate ethers and, in some cases, other viscosity-modifying agents. The result is a concrete that flows freely, yet does not allow its coarse aggregate to sink to the bottom of the mix. Self-consolidating concrete may be used where forms are crowded with steel reinforcing, making consolidation of conventional concrete difficult. The consistent surface characteristics and crisp edges produced by self-consolidating concrete make it well suited to the production of high-finish-quality architectural concrete. By eliminating the separate consolidation step and allowing more rapid placement, self-consolidating concrete can improve productivity in precast concrete and large-volume sitecast concrete operations. However, formwork costs for self-consolidating concrete may be higher than those for conventional concrete, as the greater fluid pressures exerted by the freely flowing material require forms that are especially stiff and strong.

Curing Concrete

Because concrete cures by hydration, the chemical bonding of the water and cement, and not by simple drying, it is essential that it be kept moist until its required strength is achieved. The curing reaction takes place over a very long period of time, but concrete is commonly designed on the basis of the strength that it reaches after 28 days. If it is allowed to dry out at any point during this time period, the strength of the resulting concrete will be reduced, and its surface hardness and durability are likely to be adversely affected (Figure 13.15). Concrete cast in formwork is protected from dehydration on most surfaces by the formwork, but the top surfaces must be kept moist by repeatedly spraying or flooding with water, by covering with moisture-resistant sheets of paper or film, or by spraying on a curing compound that seals the surface of the concrete against loss of moisture. These measures are even more important for concrete slabs, whose large surface areas make them especially susceptible to premature drying. Such drying is a particular danger when slabs are poured in hot or windy weather, which can cause the surface of the pour to dry out and crack even before the concrete begins to cure. Temporary windbreaks may have to be erected, shade may have to be provided, evaporation retarders may be added to the concrete, and frequent fogging of the air directly over the surface of the slab with a fine spray of water may be required until the slab is hard enough to be finished and covered or sprayed with curing compound.

At low temperatures, the curing reaction in concrete proceeds much more slowly. If concrete reaches subfreezing temperatures while curing, the curing reaction stops

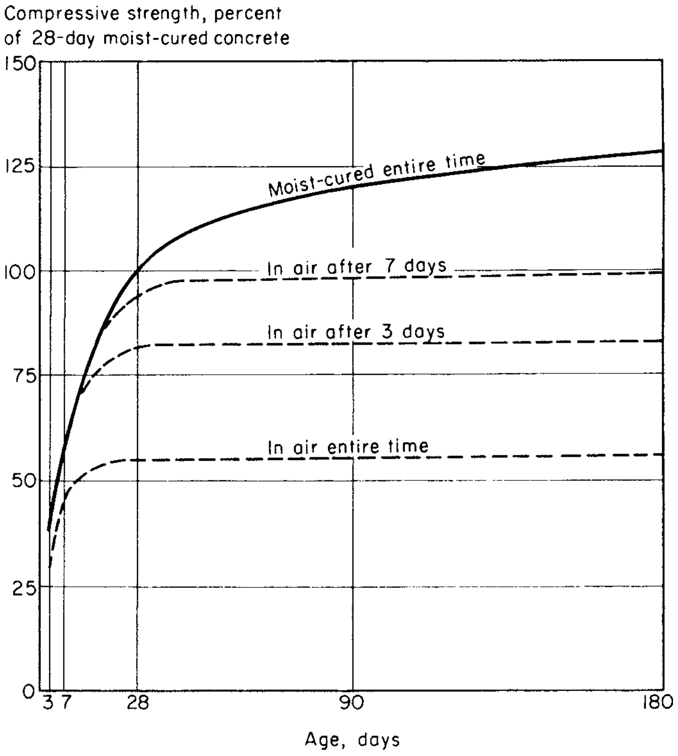


Figure 13.15
The growth of compressive strength in concrete over time. Moist-cured concrete is still gaining strength after 6 months, whereas air-dried concrete virtually stops gaining strength altogether. *(Reprinted with permission of the Portland Cement Association from* Design and Control of Concrete Mixtures, *12th edition; Photos: Portland Cement Association, Skokie, IL)*

completely until the temperature of the concrete rises above the freezing mark. It is important that the concrete be protected from low temperatures and especially from freezing until it is fully cured. If freshly poured concrete is covered and insulated, its heat of hydration is often sufficient to maintain an adequate temperature in the concrete even at fairly low air temperatures. Under more severe winter conditions, the ingredients of the concrete may have to be heated before mixing, and both a temporary enclosure and a temporary source of heat may have to be provided during placing and curing.

In very hot weather, the hydration reaction is greatly accelerated, and concrete may begin curing before there is time to place and finish it. This tendency can be controlled by using cool ingredients and, under extreme conditions, by replacing some of the mixing water with an equal quantity of crushed ice, making sure that the ice has melted fully and the concrete has been thoroughly mixed before placing. Another method of cooling concrete is to bubble liquid nitrogen through the mixture at the batch plant.

FORMWORK

Because concrete is put in place as a shapeless slurry with no physical strength, it must be shaped and supported by *formwork* until it has cured sufficiently to support itself. Formwork is usually made of braced panels of wood, metal, or plastic. It is constructed as a negative of the shape intended for the concrete. Formwork for a beam or slab serves as a temporary working surface during the construction process and as the temporary means of support for reinforcing bars. Formwork must be strong enough to support the considerable weight and fluid pressure of wet concrete without excessive deflection, which often requires temporary supports that are major structures in themselves. During curing, the formwork helps to retain the necessary water of hydration in the concrete. When curing is complete, the formwork must pull away cleanly from the concrete surfaces without damage either to the concrete or to the formwork, which is usually used repeatedly as a construction project progresses. This means that the formwork should have no reentrant corners that will trap or be trapped by the concrete. Any element of formwork that must be withdrawn directly from a location in which it is surrounded on four or more surfaces by concrete, such as a joist pan (Figures 14.23 and 14.24), must be tapered. Formwork surfaces that are in contact with concrete are also usually coated with a *form release compound*, which is an oil, wax, or plastic that prevents adhesion of the concrete to the form.

FIGURE 13.16

Casting concrete on the building site requires the construction of a complete temporary structure that will be removed once the concrete has been placed and cured.

The quality of the concrete surfaces can be no better than the quality of the forms in which they are cast, and the requirements for surface quality and structural strength of formwork are rigorous. Top-grade wooden boards and plastic-overlaid plywoods are frequently used to achieve high-quality surfaces. The ties and temporary framing members that support the boards or plywood are spaced closely to avoid bulging of the forms under the high pressure of the wet concrete.

In a sense, formwork constitutes an entire temporary building that must be erected and then demolished in order to produce a second, permanent building of concrete (Figure 13.16). The cost of this formwork accounts for a major portion often one-half or more of the overall cost of a concrete building frame. This cost is one of the factors that has led to the development of *precasting*, a process in which concrete is cast into reusable forms at an industrial plant. Rigid, fully cured structural units from the plant are then transported to the job site, where they are hoisted into place and connected much as if they were structural steel shapes. The alternative to precasting, and the more usual way of building with concrete, is *sitecasting*, also called *cast-in-place construction*, in which concrete is poured into forms that are erected on the job site. In the two chapters that follow, formwork is shown for both sitecast and precast concrete.

REINFORCING

The Concept of Reinforcing

Concrete has no useful tensile strength (Figure 13.17). Historically, its structural uses were limited until the concept of steel reinforcing was developed. The compatibility of steel and concrete is a fortuitous accident. If the two materials had grossly different coefficients of thermal expansion, a reinforced concrete structure would tear itself apart during seasonal cycles of temperature variation. If the two materials were chemically incompatible, the steel would corrode or the concrete would be degraded. If concrete did not adhere to steel, a very different and more expensive configuration of reinforcing would be necessary. Concrete and steel, however, change dimension at nearly the same rate in response to temperature changes; steel is protected from corrosion by the alkaline chemistry of concrete; and concrete bonds strongly to steel, providing a convenient means of adapting brittle concrete to structural elements that must resist not only compression, but tension, shear, and bending as well.

The basic theory of *reinforced concrete* is extremely simple: Put the reinforcing steel where there are tensile forces in a structural member, and let the concrete resist the compression. This accounts fairly precisely for the location of most of the reinforcing steel that is used in a concrete structure. However, there are some important exceptions: Steel is used to resist a share of the compression in concrete columns and in beams whose height must be reduced for architectural reasons. It is used in the form of column ties, discussed below, to prevent buckling of vertical reinforcing in columns. It is used to resist cracking that might otherwise be caused by curing shrinkage, and by thermal expansion and contraction in slabs and walls.

Material	Working Strength in Tension[a]	Working Strength in Compression[a]	Density	Modulus of Elasticity
Wood (framing lumber)	300 1000 psi 2.1 6.9 MPa	600 1700 psi 4.1 12 MPa	30 pcf 480 kg/m^3	1,000,000 1,900,000 psi 6900 13,000 MPa
Brick masonry (including mortar, unreinforced)	0	250 1300 psi 1.7 9.0 MPa	120 pcf 1900 kg/m^3	700,000 3,700,000 psi 4800 25,000 MPa
Structural steel	24,000 43,000 psi 170 300 MPa	24,000 43,000 psi 170 300 MPa	490 pcf 7800 kg/m^3	29,000,000 psi 200,000 MPa
Concrete (unreinforced)	0	1000 4000 psi 6.9 28 MPa	145 pcf 2300 kg/m^3	3,000,000 4,500,000 psi 21,000 31,000 MPa

[a] Allowable stress or approximate maximum stress under normal loading conditions.

FIGURE 13.17

Comparative physical properties of four common structural materials: wood, brick masonry, steel, and concrete (shaded row). Concrete, like masonry, has no useful tensile strength, but its compressive strength is considerable, and when combined with steel reinforcing, it can be used for every type of structure. The ranges of values in strength and stiffness reflect variations in concrete mix properties. (Specially formulated concretes are capable of substantially higher strengths than those listed in this table.)

Steel Bars for Concrete Reinforcement

Steel reinforcing bars (rebar) for concrete construction are hot-rolled in much the same way as structural shapes. They are round in cross section and *deformed* with surface ribs for better bonding to concrete (Figures 13.18 and 13.19). At the end of the rolling line in the mill, the bars are cut to a standard length (commonly 60 feet, or 18.3 m, in the United States), bundled, and shipped to local fabricating shops.

Reinforcing bars are rolled in a limited number of standard diameters. In the United States, bars are specified by a simple numbering system in which the number corresponds to the number of eighths of an inch (3.2 mm) of bar diameter (Figure 13.20). For example, a number 6 reinforcing bar is $\frac{6}{8}$ or $\frac{3}{4}$ inch (19 mm) in diameter, and a number 8 is $\frac{8}{8}$ or 1 inch (25.4 mm) in diameter. Bars larger than number 8 vary slightly from these nominal diameters in order to correspond to convenient cross-sectional areas of steel. For the increasing volume of work in the United States that is carried out in SI units, a soft conversion of units is used: The bars are exactly the same, but a different numbering system is used, corresponding roughly to the diameter of each bar in millimeters. This avoids the expensive process of converting rolling mills to produce a slightly different set of bar sizes. In most countries other than the United States, a hard metric range of reinforcing bar sizes is standard (Figure 13.21).

In selecting reinforcing bars for a given beam or column, the structural engineer knows from calculations the required cross-sectional area of steel that is needed in a given location. This area may be achieved with a larger number of smaller bars, or a smaller number of larger bars, in any of several combinations. The final bar arrangement is based on the physical space available in the concrete

FIGURE 13.18
Glowing strands of steel are reduced to reinforcing bars as they snake their way through a rolling mill. *(Courtesy of Bethlehem Steel Company)*

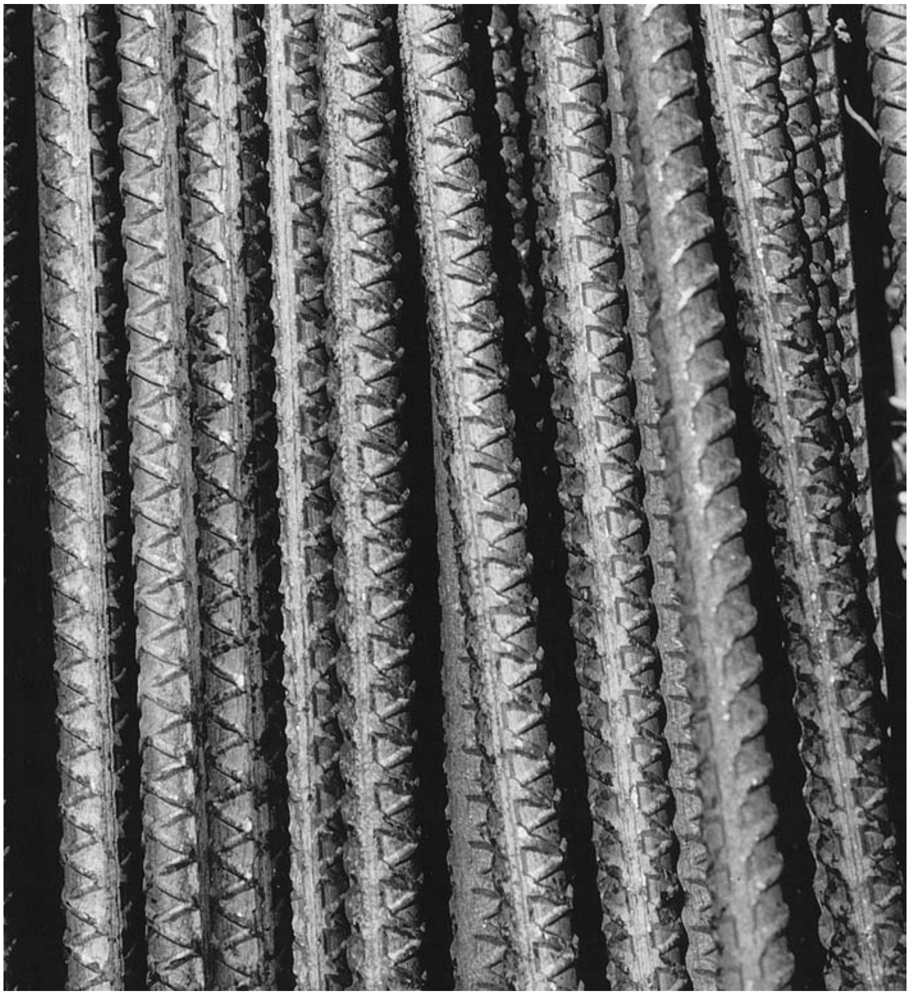


Figure 13.19
The deformations rolled onto the surface of a reinforcing bar help it to bond tightly to concrete. *(Photo by Edward Allen)*

ASTM Standard Reinforcing Bars

		Nominal Dimensions					
Bar Size		Diameter		Cross-Sectional Area		Weight	
American	Metric	in.	mm	in.^{2}	mm^2	lb/ft	kg/m
#3	#10	0.375	9.5	0.11	71	0.376	0.560
#4	#13	0.500	12.7	0.20	129	0.668	0.944
#5	#16	0.625	15.9	0.31	199	1.043	1.552
#6	#19	0.750	19.1	0.44	284	1.502	2.235
#7	#22	0.875	22.2	0.60	387	2.044	3.042
#8	#25	1.000	25.4	0.79	510	2.670	3.973
#9	#29	1.128	28.7	1.00	645	3.400	5.060
#10	#32	1.270	32.3	1.27	819	4.303	6.404
#11	#36	1.410	35.8	1.56	1006	5.313	7.907
#14	#43	1.693	43.0	2.25	1452	7.65	11.38
#18	#57	2.257	57.3	4.00	2581	13.6	20.24

Figure 13.20
American standard sizes of reinforcing bars. These sizes were originally established in conventional units of inches and square inches. More recently, soft metric designations have also been given to the bars without changing their sizes. Notice that the size designations of the bars in both systems of measurement correspond very closely to the rule-of-thumb values of 1/8 inch or 1 mm per bar size number.

Metric Reinforcing Bars

		Nominal Dimensions	
Size Designation	Nominal Mass, kg/m	Diameter, mm	Cross Sectional Area, mm^2
10M	0.785	11.3	100
15M	1.570	16.0	200
20M	2.355	19.5	300
25M	3.925	25.2	500
30M	5.495	29.9	700
35M	7.850	35.7	1000
45M	11.775	43.7	1500
55M	19.625	56.4	2500

Figure 13.21
These hard metric reinforcing bar sizes are used in most countries of the world.

member, the required depth of concrete that must cover the reinforcing, the clear spacing required between bars to allow passage of the concrete aggregate, and the sizes and number of bars that will be most convenient to fabricate and install.

Most reinforcing bars are manufactured according to ASTM standard A615 and are available in grades 40, 60, and 75, corresponding to steel with yield strengths of 40,000, 60,000, and 75,000 psi (280, 420, and 520 MPa), respectively (Figure 13.22). Grade 60 is generally the most economical and readily available of the three, although grade 75 is finding increasing use in column reinforcing. Reinforcing bars conforming to ASTM A706, made with low-alloy steel meeting special ductility requirements, are used where concrete structures must meet special seismic design criteria or where extensive welding of reinforcing is required. In structures with especially heavy reinforcing requirements, reinforcing bars conforming to ASTM A1035 with strengths as high as 120,000 psi (830 MPa) may be used. With such high-strength bars, bar size may be reduced and the spacing between the bars may be increased in comparison to designs with conventional-strength reinforcing. This reduces *rebar congestion*, making it easier to place and consolidate the concrete around the reinforcing.

Reinforcing bars in concrete structures that are exposed to salts such as deicing salts or those in seawater are prone to rust. Galvanized reinforcing bars and epoxy-coated reinforcing bars are often used in marine structures, highway structures, and parking garages to resist this corrosion. Stainless steel bars, stainless-steel-clad bars, zinc-and-polymer-coated bars, and proprietary corrosion-resistant alloy bars are newer types of corrosion-resistant reinforcing. Still in the experimental stage or newest to market are nonmetallic reinforcing bars made from high-strength fibers of carbon, aramid, or glass embedded in a polymeric matrix.

As an alternative to conventional reinforcing bars, reinforcing steel for slabs is produced in sheets or rolls of *welded wire reinforcing (WWR)*, also called *welded wire fabric (WWF)*, a grid of wires or round bars spaced 2 to 12 inches (50 300 mm) apart (Figure 13.23). The lighter styles of welded wire fabric resemble cattle fencing and are used to reinforce concrete slabs on grade and certain precast concrete elements. The heavier styles find use in concrete walls and structural slabs. The principal advantage of welded wire fabric over individual bars is economy of labor in placing the reinforcing, especially where a large number of small bars can be replaced by a single sheet of material. The size and spacing of the wires or bars for a particular application are specified by the structural engineer or architect of the building.

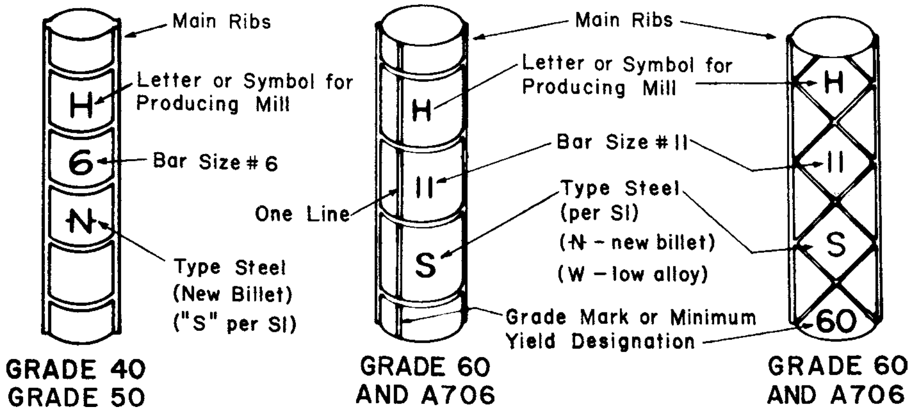


FIGURE 13.22
Reinforcing bars are manufactured with identification marks, denoting the mill that produced the bars, bar size, type of steel, and steel grade. Steel grade is indicated either with a number, such as 60 for Grade 60 steel, or with short bars (grade lines), in which no bars indicates Grade 40 or 50 steel, one bar indicates Grade 60 steel, and two bars indicates grade 75 steel. *(Courtesy of Concrete Reinforcing Steel Institute)*

Sectional Area and Weight of Welded Wire Reinforcing

Wire Size Number		Nominal Diameter, in.	Nominal Weight, lb/lin ft	Area in Square Inches per Foot of Width for Various Spacings						
				Center-Center Spacing						
Smooth	Deformed			2	3	4	6	8	10	12
W20	D20	0.505	.680	1.20	.80	.60	.40	.30	.24	.20
W18	D18	0.479	.612	1.08	.72	.54	.36	.27	.216	.18
W16	D16	0.451	.544	.96	.64	.48	.32	.24	.192	.16
W14	D14	0.422	.476	.84	.56	.42	.28	.21	.168	.14
W12	D12	0.391	.408	.72	.48	.36	.24	.18	.144	.12
W11	D11	0.374	.374	.66	.44	.33	.22	.165	.132	.11
W10.5		0.366	.357	.63	.42	.315	.21	.157	.126	.105
W10	D10	0.357	.340	.60	.40	.30	.20	.15	.12	.10
W9.5		0.348	.323	.57	.38	.285	.19	.142	.114	.095
W9	D9	0.338	.306	.54	.36	.27	.18	.135	.108	.09
W8.5		0.329	.289	.51	.34	.255	.17	.127	.102	.085
W8	D8	0.319	.272	.48	.32	.24	.16	.12	.096	.08
W7.5		0.309	.255	.45	.30	.225	.15	.112	.09	.075
W7	D7	0.299	.238	.42	.28	.21	.14	.105	.084	.07
W6.5		0.288	.221	.39	.26	.195	.13	.097	.078	.065
W6	D6	0.276	.204	.36	.24	.18	.12	.09	.072	.06
W5.5		0.265	.187	.33	.22	.165	.11	.082	.066	.055
W5	D5	0.252	.170	.30	.20	.15	.10	.075	.06	.05
W4.5		0.239	.153	.27	.18	.135	.09	.067	.054	.045
W4	D4	0.226	.136	.24	.16	.12	.08	.06	.048	.04
W3.5		0.211	.119	.21	.14	.105	.07	.052	.042	.035
W3		0.195	.102	.18	.12	.09	.06	.045	.036	.03
W2.9		0.192	.099	.174	.116	.087	.058	.043	.035	.029
W2.5		0.178	.085	.15	.10	.075	.05	.037	.03	.025
W2.1		0.162	.070	.126	.084	.063	.042	.031	.025	.021
W2		0.160	.068	.12	.08	.06	.04	.03	.024	.02
W1.5		0.138	.051	.09	.06	.045	.03	.022	.018	.015
W1.4		0.134	.048	.084	.056	.042	.028	.021	.017	.014

FIGURE 13.23

Standard configurations of welded wire reinforcing. The heaviest wires are more than ½ inch (13 mm) in diameter, making them suitable for structural slab reinforcing. Welded wire reinforcing is specified by first indicating the spacing of the wires and then the wire types. For example, the designation *6 × 12-W12 × W5* indicates welded wire reinforcing with W12 longitudinal wires spaced at 6 inches (150 mm) and W5 transverse wires spaced at 12 inches (300 mm). *(Courtesy of Concrete Reinforcing Steel Institute)*

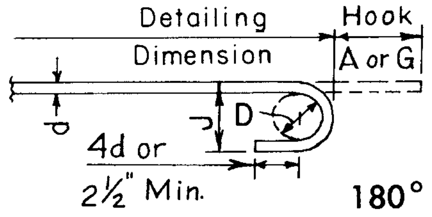
STANDARD HOOKS

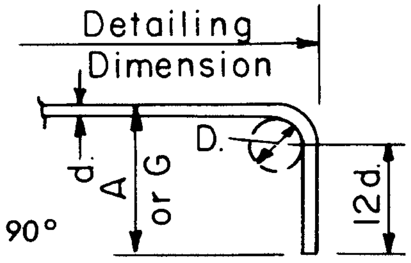
All specific sizes recommended by CRSI below meet minimum requirements of ACI 318

RECOMMENDED END HOOKS
All Grades

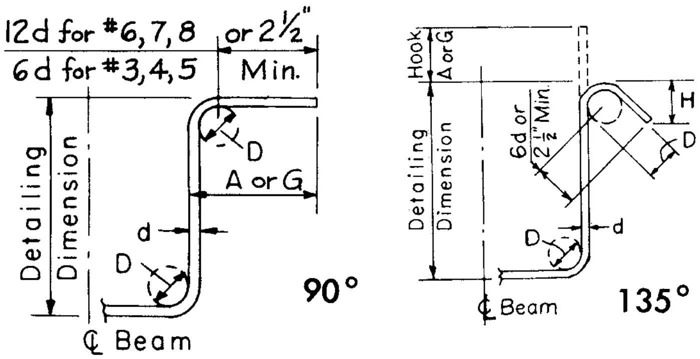
D=Finished bend diameter

Bar Size	180° HOOKS			90° HOOKS
	D	A or G	J	A or G
# 3	2¼	5	3	6
# 4	3	6	4	8
# 5	3¾	7	5	10
# 6	4½	8	6	1-0
# 7	5¼	10	7	1-2
# 8	6	11	8	1-4
# 9	9½	1-3	11¾	1-7
#10	10¾	1-5	1-1¼	1-10
#11	12	1-7	1-2¾	2-0
#14	18¼	2-3	1-9¾	2-7
#18	24	3-0	2-4½	3-5



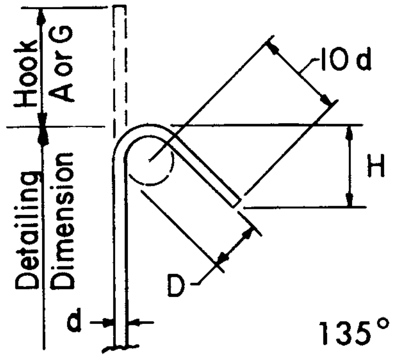


STIRRUP AND TIE HOOKS



STIRRUPS
(TIES SIMILAR)

135° SEISMIC STIRRUP/TIE HOOKS



STIRRUP AND TIE HOOK DIMENSIONS
Grades 40-50-60 ksi

Bar Size	D (in.)	90° Hook	135° Hook	
		Hook A or G	Hook A or G	H Approx.
#3	1½	4	4	2½
#4	2	4½	4½	3
#5	2½	6	5½	3¾
#6	4½	1-0	7¾	4½
#7	5¼	1-2	9	5¼
#8	6	1-4	10¼	6

135° SEISMIC STIRRUP/TIE HOOK DIMENSIONS
Grades 40-50-60 ksi

Bar Size	D (in.)	135° Hook	
		Hook A or G	H Approx.
#3	1½	5	3½
#4	2	6½	4½
#5	2½	8	5½
#6	4½	10¾	6½
#7	5¼	1-0½	7¾
#8	6	1-2¼	9

FIGURE 13.24
The bending of reinforcing bars is done according to precise standards in a fabricator s shop. *(Courtesy of Concrete Reinforcing Steel Institute)*

Fabrication and Erection of Reinforcing Bars

The fabrication of reinforcing steel for a concrete construction project is analogous to the fabrication of steel shapes for a steel frame building (Chapter 11). The fabricator receives the engineering drawings for the building from the contractor and prepares shop drawings for the reinforcing bars. After the shop drawings have been checked by the engineer or architect, the fabricator sets to work cutting the reinforcing bar stock to length, making the necessary bends (Figure 13.24) and tying the fabricated bars into bundles that are tagged to indicate their destination in the building. The bundles are shipped to the building site as needed. There they are broken down, lifted by hand or hoisted by crane, and wired (or occasionally welded) together in the forms to await pouring of the concrete. The wire has a temporary function only, which is to hold the reinforcement in position until the concrete has cured. Any transfer of load from one reinforcing bar to another in the completed building is done by the concrete. Where two bars must be spliced, they are overlapped a specified number of bar diameters (typically 30), and the loads are transferred from one to the other by the surrounding concrete. The one common exception occurs in heavily reinforced columns where there is insufficient space to overlap the bars; there they are often spliced end to end rather than overlapped, and loads are transferred through welds or sleevelike mechanical splicing devices (Figure 13.25).

The composite action of concrete and steel in reinforced concrete structural elements is such that the reinforcing steel is usually loaded axially in tension or compression, and occasionally in shear, but never in bending. The bending stiffness of the reinforcing bars themselves is of no consequence in imparting strength to the concrete.

FIGURE 13.25
Some mechanical devices for splicing reinforcing bars. From left to right: A lapped, wedged connection, used primarily to connect new bars to old ones when adding to an existing structure. A welded connector, very strong and tough. A grouted sleeve connector for joining precast concrete components: One bar is threaded and screwed into a collar at one end of the sleeve, and the other bar is inserted into the remainder of the sleeve and held there with injected grout. A threaded sleeve, with both bars threaded and screwed into the ends of the sleeve. A simple clamping sleeve that serves to align compression bars in a column. A flanged coupler for splicing bars at the face of a concrete wall or beam: The coupler is screwed onto the threaded end of one bar, and its flange is nailed to the inside face of the formwork. After the formwork has been stripped, the other bar is threaded and screwed through a hole in the flange and into the coupler. *(Photo courtesy of Erico, Inc.)*

Reinforcing a Simple Concrete Beam

In an ideal, simply supported beam under uniform loading, compressive (squeezing) forces follow a set of archlike curves that create a maximum compressive stress in the top of the beam at midspan, with progressively lower compressive stresses toward either end. A mirrored set of curves correspond to paths of tensile (stretching) force, with stresses again reaching a maximum at the middle of the span (Figure 13.26). In an ideally reinforced concrete beam, steel reinforcing bars would be bent to follow these lines of tension, and the bunching of the bars at midspan would serve to resist the higher stresses at that point. It is difficult, however, to bend bars into these curves and to support the curved bars adequately in the formwork, so a simpler rectilinear arrangement of reinforcing steel is substituted.

This arrangement consists of a set of bottom bars and stirrups. The *bottom bars* are placed horizontally near the bottom of the beam, leaving a specified amount of concrete below and to the sides of the rods as *cover* (Figure 13.27). The concrete cover provides a full embedment for the reinforcing bars and protects them against fire and corrosion. The bars are most heavily stressed at the midpoint of the beam span, with progressively smaller amounts of stress

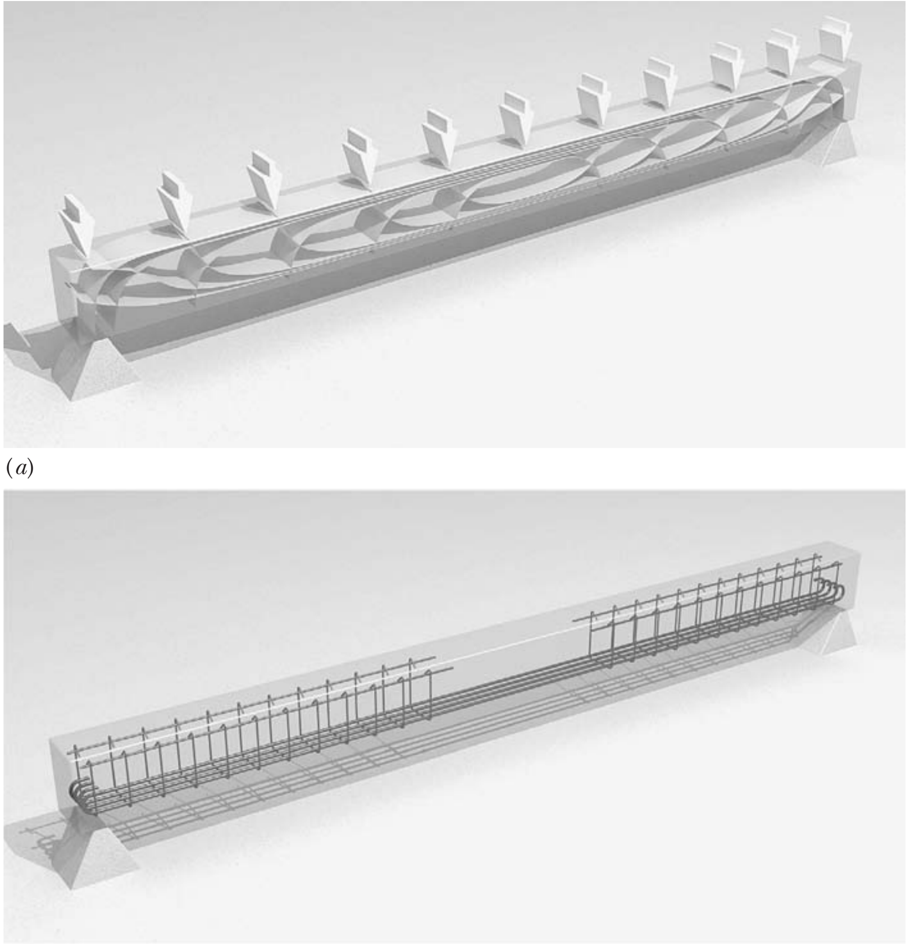


FIGURE 13.26
(*a*) The directions of force in a simply supported (supported at the ends only) beam under uniform loading. The archlike lines represent compression, and the cablelike lines represent tension. Near the ends of the beam, the lines of strongest tensile force move upward diagonally through the beam. (*b*) Steel reinforcing for a simply supported beam under uniform loading. The concrete resists compressive forces. The horizontal bars near the bottom of the beam resist the major tensile forces. The vertical stirrups resist the lesser diagonal tensile forces near the ends of the beam.

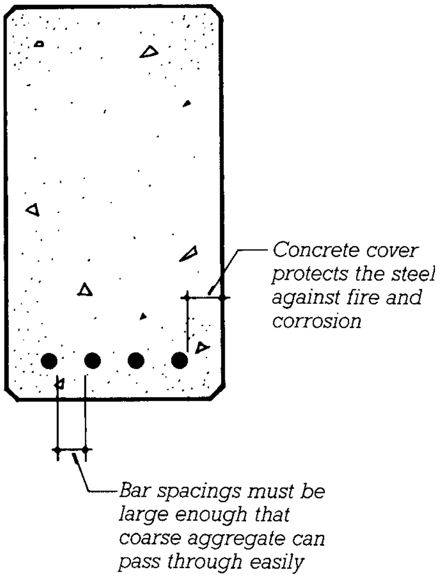


FIGURE 13.27
A cross section of a rectangular concrete beam showing cover and bar spacing.

toward each of the supports. The differences in stress are dissipated from the bars into the concrete by means of *bond* forces, the adhesive forces between the concrete and the steel, aided by the ribs on the surface of the bars. At the ends of the beam, some stress remains in the steel, but there is no further length of concrete into which the stress can be dissipated. This problem is solved by bending the ends of the bars into *hooks,* which are semicircular bends of standard dimensions.

The bottom bars do the heavy tensile work in the beam, but some lesser tensile forces occur in a diagonal orientation near the ends of the beam. These are resisted by a series of *stirrups* (Figure 13.26). The stirrups may be either open *U-stirrups,* as shown, or *closed stirrup-ties,* which are full rectangular loops of steel that wrap all the way around the longitudinal bars. U-stirrups are less expensive to make and install and are sufficient for many situations, but stirrup-ties are required in beams that will be subjected to torsional (twisting) forces or to high compressive forces in the top or bottom bars. In either case, the stirrups furnish vertical tensile reinforcing to resist the cracking forces that run diagonally across them. A more efficient use of steel would be to use diagonal stirrups oriented in the same direction as the diagonal tensile forces, but they would be difficult to install.

When the simple beam of our example is formed, the bottom steel is supported at the correct cover height by *chairs* made of heavy steel wire or plastic (Figures 13.28 and 13.29). In a broad beam or slab, bars are supported by long chairs called *bolsters*. Chairs and bolsters remain in the concrete after pouring, even though their work is finished, because there is no way to get them out. In outdoor concrete work, the feet of the chairs and bolsters sometimes rust where they come in contact with the face of the beam or slab unless plastic or plastic-capped steel chairs are used. Where reinforced concrete is poured in direct contact with the soil, concrete bricks or small pieces of concrete are used to support the bars instead of chairs to prevent rust from forming under the feet of the chairs and spreading up into the reinforcing bars.

The stirrups in the simple beam that we have been examining are supported by wiring them to the bottom bars and by tying their tops to horizontal #3 top bars (the smallest standard size) that have no function in the beam other than to keep the stirrups upright and properly spaced until the concrete has been poured and cured.

FIGURE 13.28

A two-piece plastic bar support, called a tower chair, supports a steel reinforcing bar for a structural concrete slab. To the left of the chair, a small concrete brick supporting a second bar in a position closer to the bottom of the slab is also partially visible. *(Photo by Joseph Iano)*

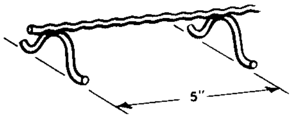
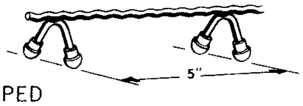
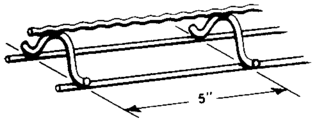
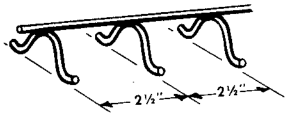
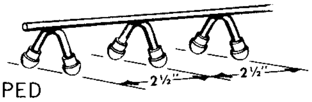
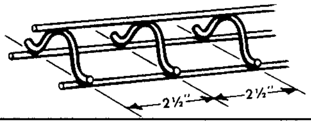
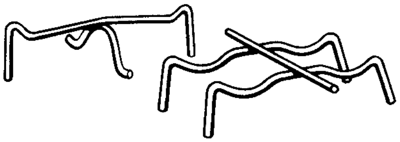
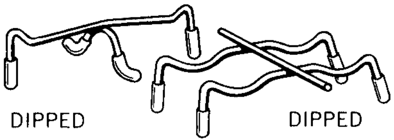
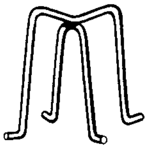
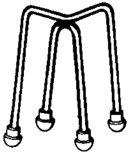
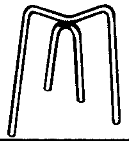
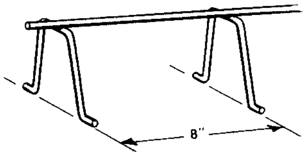
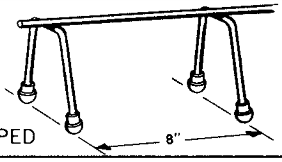
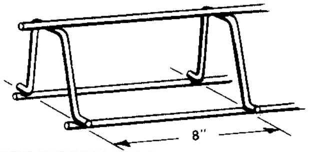
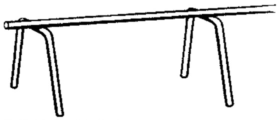
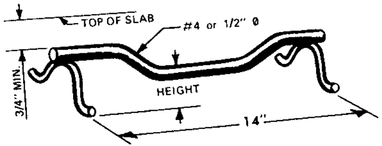
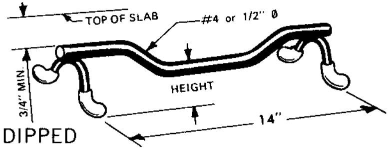
SYMBOL	BAR SUPPORT ILLUSTRATION	BAR SUPPORT ILLUSTRATION PLASTIC CAPPED OR DIPPED	TYPE OF SUPPORT	SIZES
SB		 CAPPED	Slab Bolster	¾, 1, 1½, and 2 inch heights in 5 ft. and 10 ft. lengths
SBU			Slab Bolster Upper	Same as SB
BB		 CAPPED	Beam Bolster	1, 1½, 2, over 2″ to 5″ heights in increments of ¼″ in lengths of 5 ft.
BBU			Beam Bolster Upper	Same as BB
BC		DIPPED 	Individual Bar Chair	¾, 1, 1½, and 1¾″ heights
JC		 DIPPED DIPPED	Joist Chair	4, 5, and 6 inch widths and ¾, 1 and 1½ inch heights
HC		CAPPED 	Individual High Chair	2 to 15 inch heights in increments of ¼ inch
HCM			High Chair for Metal Deck	2 to 15 inch heights in increments of ¼ in.
CHC		 CAPPED	Continuous High Chair	Same as HC in 5 foot and 10 foot lengths
CHCU			Continuous High Chair Upper	Same as CHC
CHCM			Continuous High Chair for Metal Deck	Up to 5 inch heights in increments of ¼ in.
JCU		 DIPPED	Joist Chair Upper	14″ span. Heights − 1″ thru +3½″ vary in ¼″ increments

FIGURE 13.29
Chairs and bolsters for supporting reinforcing bars in beams and slabs. Bolsters and continuous chairs are made in long lengths for use in slabs. Chairs support only one or two bars each. *(Courtesy of Concrete Reinforcing Steel Institute)*

Reinforcing a Continuous Concrete Beam

Most sitecast concrete beams are not of this simple type because concrete lends itself most easily to one-piece structural frames with a high degree of structural continuity from one beam span to the next. In a continuous structure, the bottom of the beam is in tension at midspan, and the top of the beam is in tension at supporting girders, columns, or walls. This means that top bars must be provided over the supports, and bottom bars in midspan, along with the usual stirrups, as illustrated in Figure 13.30. Until a few decades ago, it was common practice to bend some of the horizontal bars up or down at the points of bending reversal in continuous concrete beams so that the same bars could serve both as bottom steel at midspan and as top steel over the columns, but this has largely been abandoned in favor of the simpler practice of using only straight bars for horizontal reinforcing.

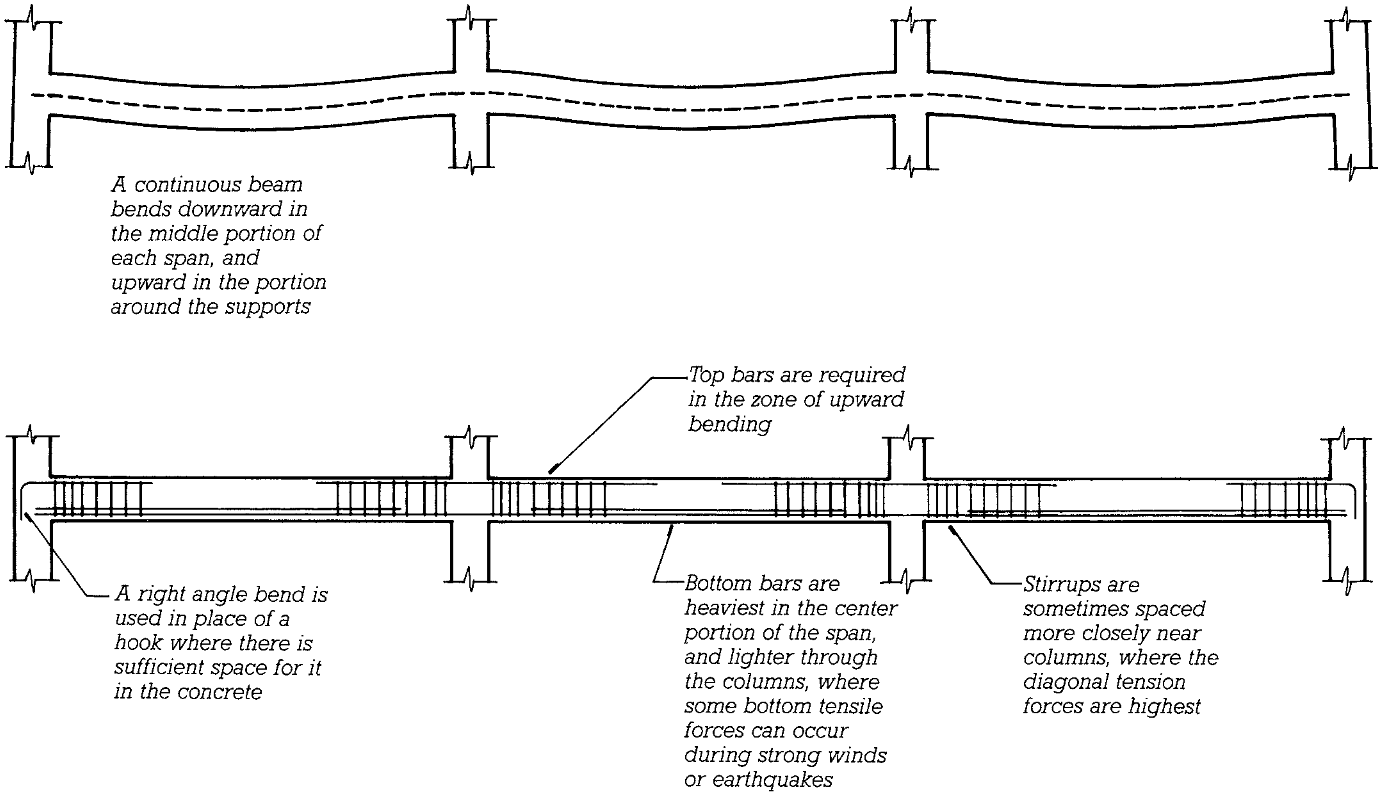


FIGURE 13.30
Reinforcing for a concrete beam that is continuous across several spans. The upper diagram shows in exaggerated form the shape taken by a continuous beam under uniform loading; the broken line is the centerline of the beam. The lower diagram shows the arrangement of bottom steel, top steel, and stirrups conventionally used in this beam. The bottom bars are usually placed on the same level, but they are shown on two levels in this diagram to demonstrate the way in which some of the bottom steel is discontinued in the zones near the columns. There is a simple rule of thumb for determining where the bending steel must be placed in a beam: Draw an exaggerated diagram of the shape the beam will take under load, as in the top drawing of this illustration, and put the bars as close as possible to the convex edges.

Reinforcing Structural Concrete Slabs

A concrete slab that spans across parallel beams (*one-way action*) is, in effect, a very wide beam. The reinforcing pattern for such a slab is similar to the reinforcing pattern in a beam, but with a larger number of smaller top and bottom bars distributed evenly across the width of the slab. Because the slab is wide, it has a large cross-sectional area of concrete that can usually resist the relatively weak diagonal tension forces near its supports without the aid of stirrups.

One-way slabs must be provided with *shrinkage–temperature steel,* a set of small-diameter reinforcing bars set at right angles to, and on top of, the primary reinforcing in the slab. Their function is to prevent cracks from forming parallel to the primary reinforcing because of concrete shrinkage, temperature-induced stresses, or miscellaneous forces that may occur in the building (Figure 13.31).

Two-Way Slab Action

A structural economy unique to concrete frames is realized through the use of *two-way action* in floor and roof slabs. Two-way slabs, which work best for bays that are square or nearly square, are reinforced equally in both directions and share the bending forces equally between the two directions. This allows two-way slabs to be somewhat shallower than one-way slabs, to use less reinforcing steel, and thus to cost less. Figure 13.32 illustrates the concept of two-way action. Several different two-way concrete framing systems will be shown in detail in the next chapter.

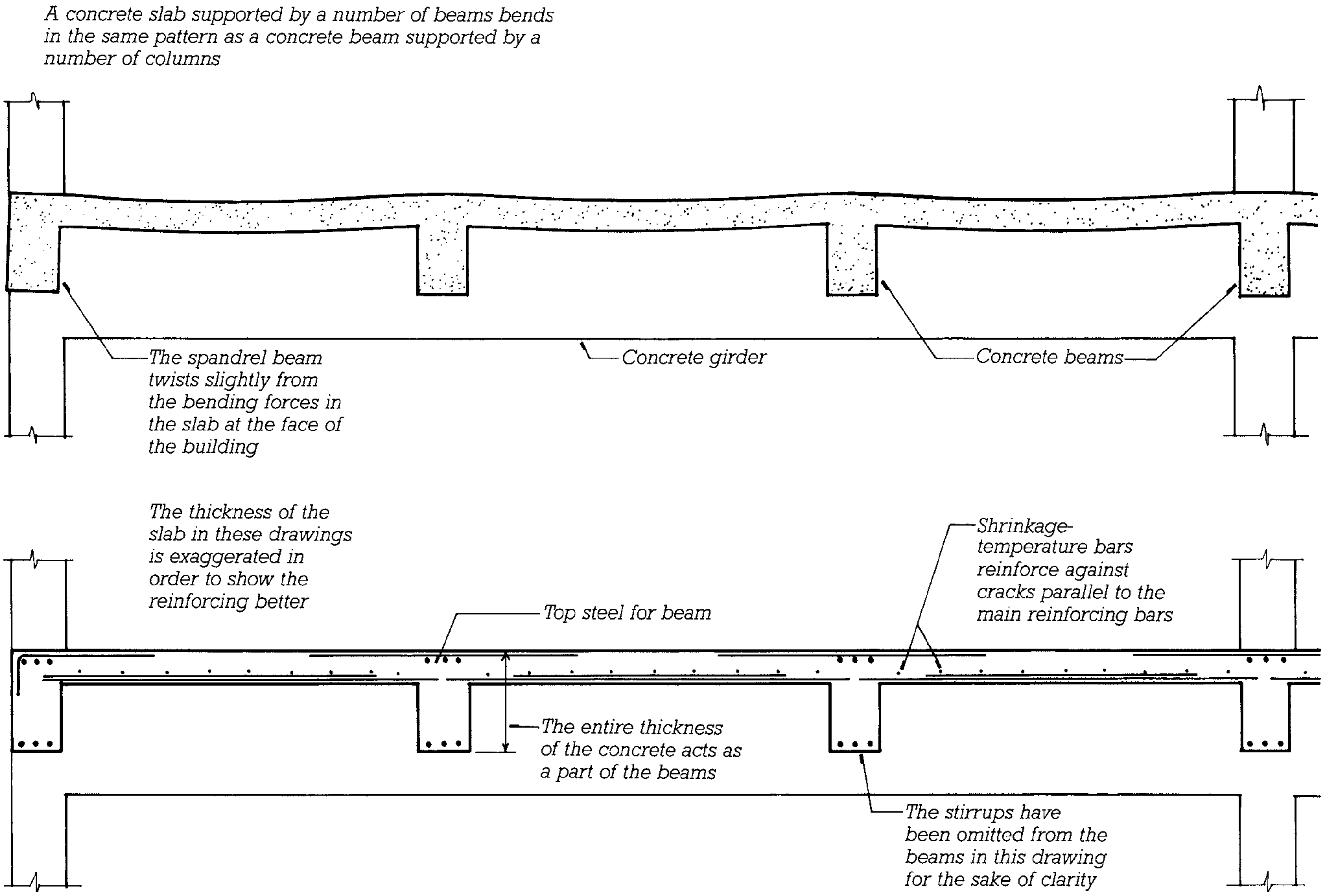
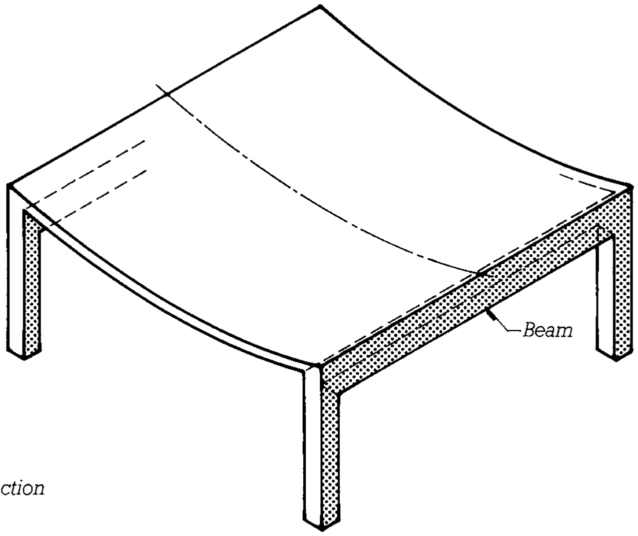


FIGURE 13.31

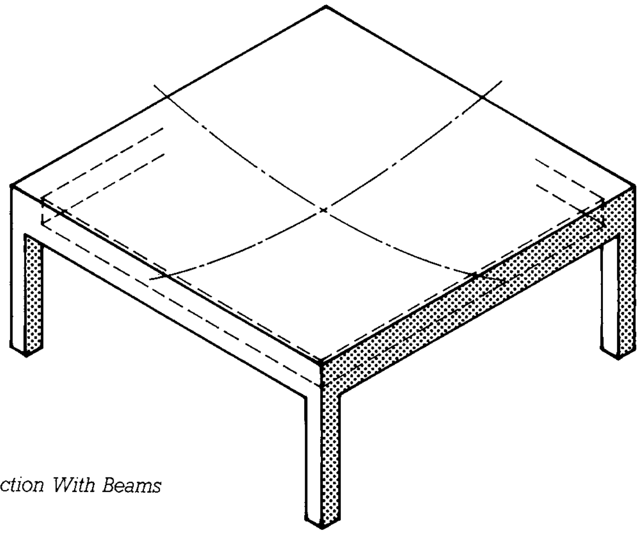
Reinforcing for a one-way concrete slab. The reinforcing is similar to that for a continuous beam, except that stirrups are not usually required in the slab, and shrinkage temperature bars must be added in the perpendicular direction. The slab does not sit on the beams; rather, the concrete around the top of a beam is part of both the beam and the slab. A concrete beam in this situation is considered to be a T-shaped member, with a portion of the slab acting together with the stem of the beam, resulting in greater structural efficiency and reduced beam depth.

The country . . . near Taliesin my home and workshop, is the bed of an ancient glacier drift. Vast busy gravel pits abound there, exposing heaps of yellow aggregate once and still everywhere near, sleeping beneath the green fields. Great heaps, clean and golden, are always waiting there in the sun. And I never pass . . . without an emotion, a vision of the long dust-whitened stretches of the cement mills grinding to impalpable fineness the magic powder that would "set" my vision all to shape; I wish both mill and gravel endlessly subject to my will. . . . Materials! What a resource.

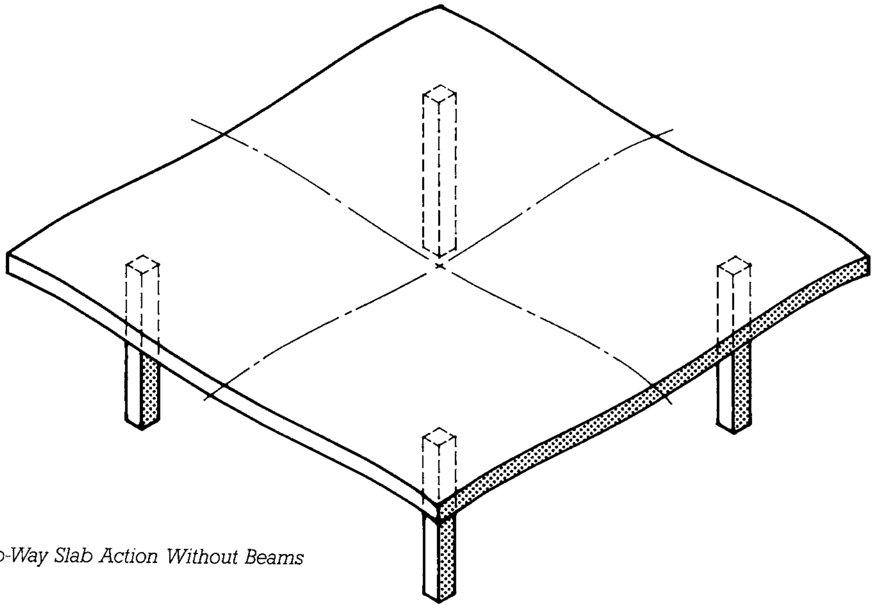
Frank Lloyd Wright *Architectural Record, October 1928.*



One-Way Slab Action



Two-Way Slab Action With Beams



Two-Way Slab Action Without Beams

FIGURE 13.32
One-way and two-way slab action, with deflections greatly exaggerated.

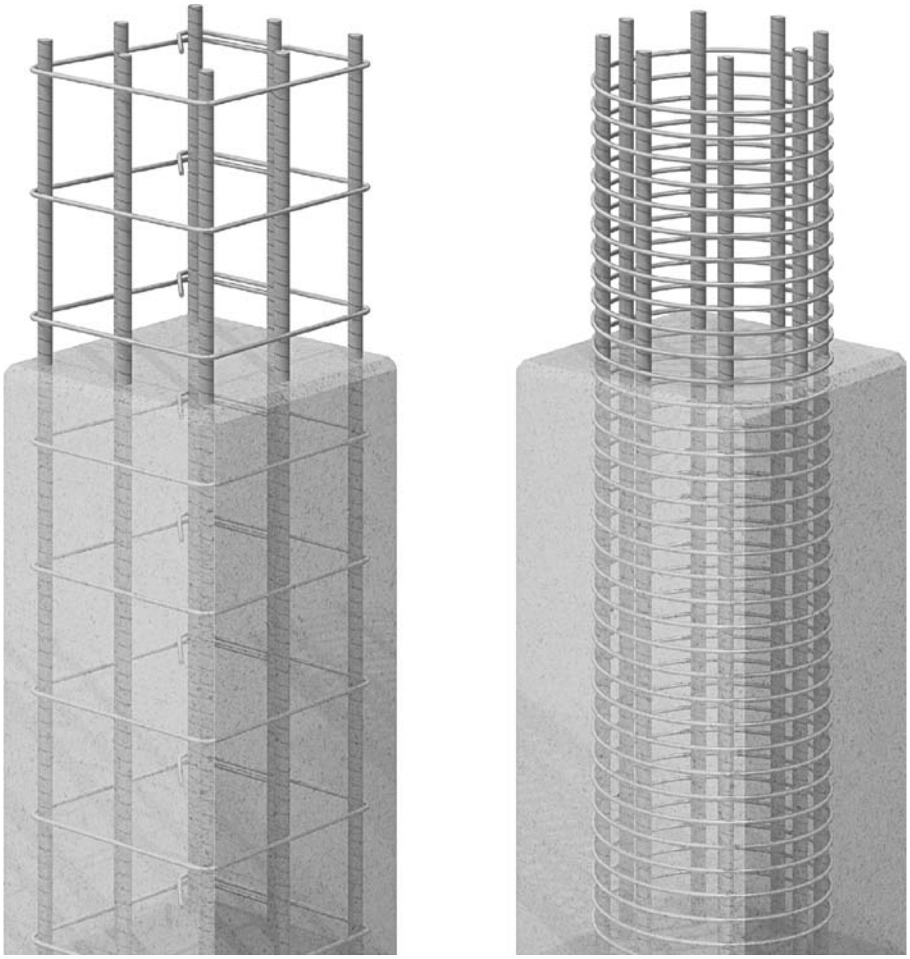


FIGURE 13.33
Reinforcing for concrete columns. To the left is a column with a rectangular arrangement of vertical bars and column ties. To the right is a circular arrangement of vertical bars with a column spiral. Either arrangement may be used in either a round or a square column.

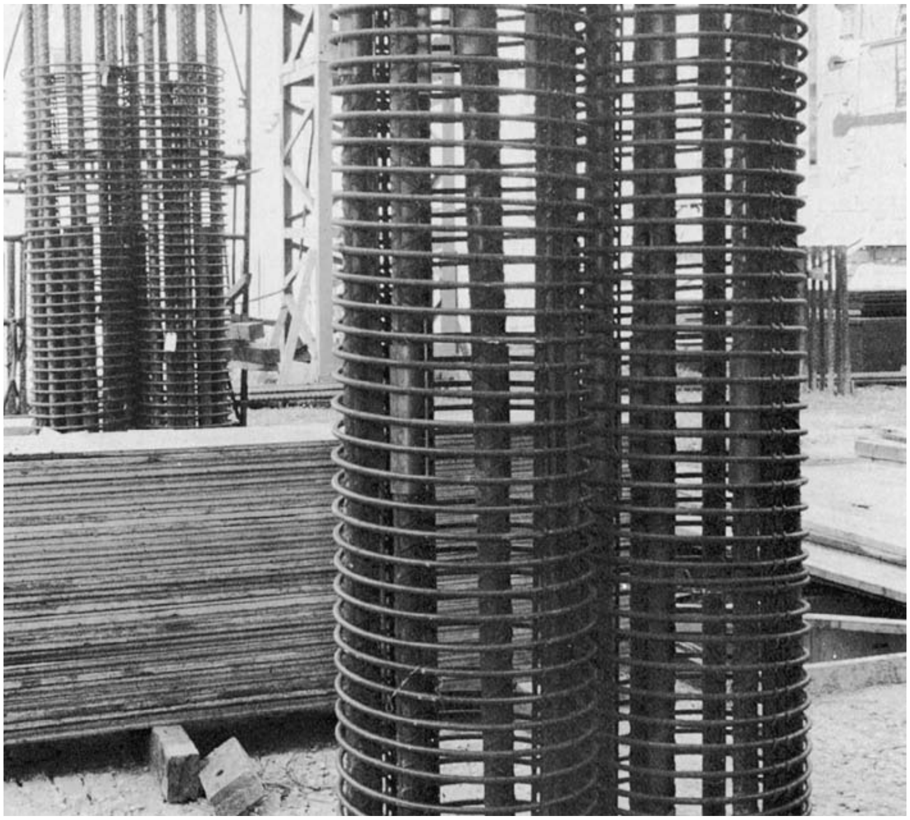


Figure 13.34
Column spirals. Each double circle of vertical bars will be embedded in a single rectangular column. *(Courtesy of Concrete Reinforcing Steel Institute)*

Reinforcing Concrete Columns

Columns contain two types of reinforcing: *Vertical bars* (also called *column bars*) are large-diameter reinforcing bars that share the compressive loads with the concrete and resist the tensile stresses that occur in columns when a building frame is subjected to wind or earthquake forces. *Ties* of small-diameter steel bars wrapped around the vertical bars help to prevent them from buckling under load: Inward buckling is prevented by the concrete core of the column and outward buckling by the ties (Figures 13.33 and 13.34). The vertical bars may be arranged either in a circle or in rectangular patterns. The ties may be either of two types: *column ties* or *column spirals*. Spirals are shipped to the construction site as tight coils of rod that are expanded accordion fashion to the required spacing and wired to the vertical bars. They are generally used only for square or circular arrangements of vertical bars. For rectangular arrangements of vertical bars, discrete column ties must be wired to the vertical bars one by one. Each corner bar and alternate interior bars must be contained inside a bend of each tie, so two or more column ties are often attached at each level (Figure 13.35). A circular arrangement of vertical bars is often more economical than a rectangular one because it avoids the need to enclose bars in the corners of ties. Column ties are generally more economical than spirals, so even columns with circular bar arrangements are often tied with discrete circular ties. The sizes and spacings of column ties and spirals are determined by the structural engineer. To minimize labor costs on the job site, the ties and vertical bars for each column are usually wired together in a horizontal position at ground level, and the finished column cage is lifted into its final position with a crane.

Fibrous Reinforcing

Fibrous reinforcing is composed of short fibers of glass, steel, or polypropylene that are added to a concrete mix. *Microfiber reinforcing* is added in relatively low dosages and is intended to reduce *plastic shrinkage cracking*, which frequently occurs while the concrete is still in a plastic state, during the earliest stages of curing. Microfiber reinforcing makes little if any contribution to the properties of fully cured concrete. *Macrofiber reinforcing*, usually of polypropylene or a steel-polypropylene blend, not only protects against plastic shrinkage but also resists longer-term cracking due to drying shrinkage and thermal stresses. Macrofiber reinforcing is added to concrete at dosages 10 or 20 times greater than those of microfiber reinforcing and, in some cases, fully replaces the usual shrinkage temperature steel in concrete slabs. Macrofiber reinforcing can also improve concrete's resistance to impact, abrasion, and shock. Glass fibers are also added to concrete to produce glass-fiber-reinforced concrete (GFRC), which is used for cladding panels (see Chapter 20).

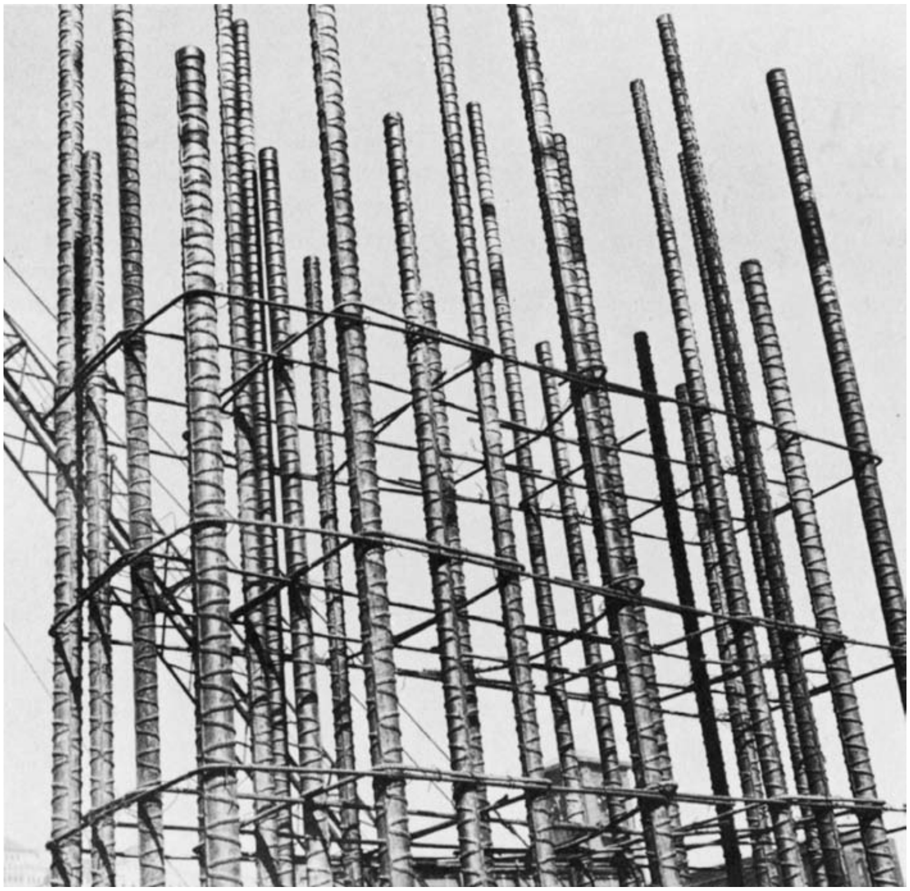


FIGURE 13.35
Multiple column ties at each level are arranged so that the four corner bars and alternate interior bars are contained in the corners of the ties. *(Courtesy of Concrete Reinforcing Steel Institute)*

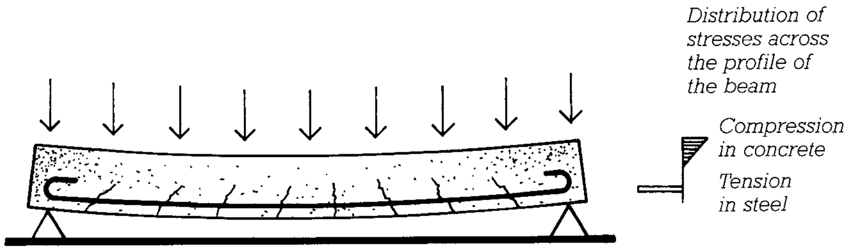
CONCRETE CREEP

In addition to plastic and drying shrinkage, concrete is subject to long-term *creep*. When placed under sustained compressive stress from its own weight, the weight of other permanent building components, or the force of prestressing (as described later in this chapter), concrete will gradually and permanently shorten over a period of months or years. In some circumstances, this dimensional change is of sufficient magnitude that it must be accounted for in the design and detailing of building systems. For example, when a brick veneer cladding system (see Chapter 20) is supported on a concrete building frame, the shrinkage of the concrete combined with other factors affecting movement of the masonry require that horizontal movement joints be designed into the cladding system to accommodate the differential movement between the cladding and the building structure. If these joints are not provided, or if they are too narrow and have insufficient capacity to absorb movement, the cladding system can fail as it becomes compressed, in part, by the shortening of the concrete structure. As a rule of thumb, sitecast concrete building frames can be expected to shorten in height under the influence of their own weight and other dead loads at the rate of 1⁄16 inch for every 10 feet (½ mm per meter) of building height.

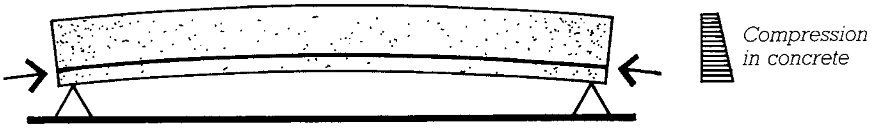
PRESTRESSING

When a beam supports a load, the compression side of the beam is squeezed slightly and the tension side is stretched. In a reinforced concrete beam, the stretching tendency is resisted by the reinforcing steel but not by the brittle concrete. When the steel elongates (stretches) under tension, the concrete around it forms cracks that run from the edge of the beam to the horizontal plane in the beam, above which compressive forces occur. This cracking is visible to the unaided eye in reinforced concrete beams that are loaded to (or beyond) their full load-carrying capacity. In effect, over half of the concrete in the beam is doing no useful work except to hold the steel in position and protect it from fire and corrosion (Figure 13.36).

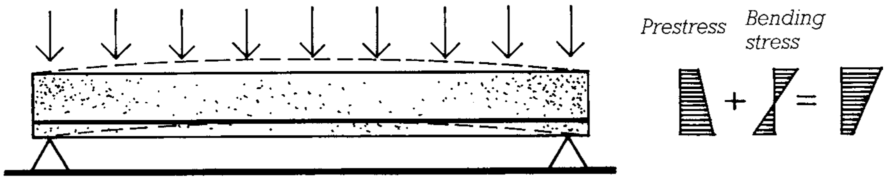
If the reinforcing bars could be stretched to a high tension before the beam is loaded and then released against the concrete that surrounds them, they would place the concrete in compression. If a load were subsequently put on the beam, the tension in the stretched steel would increase further, and the compression in the concrete surrounding the steel would diminish. If the initial tension or *prestress* in the steel bars were of sufficient magnitude, however, the surrounding concrete would never be subjected to tension, and no cracking would occur. Furthermore, the



In a reinforced concrete beam, less than half the concrete is in compression, and cracks will appear in the bottom of the beam under full load



When a concrete beam is prestressed, all the concrete acts in compression. The off-center location of the prestressing steel causes a camber in the beam



Under loading, the prestressed beam becomes flatter, but all the concrete still acts in compression, and no cracks appear

FIGURE 13.36

The rationale for prestressing concrete. In addition to the absence of cracks in the prestressed beam, the structural action is more efficient than that of a reinforced beam. Therefore, the prestressed beam uses less material. The small diagrams to the right indicate the distribution of stresses across the vertical cross section of each of the beams at midspan.

beam would be capable of carrying a much greater load with the same amounts of concrete and steel than if it were merely reinforced in the conventional manner. This is the rationale for *prestressed concrete*. Prestressed members, particularly those designed to work in bending, contain less concrete than reinforced members of equivalent strength and thus are, in general, less expensive. Their lighter weight also pays off by making precast, prestressed concrete members easier and cheaper to transport. For this reason, structural precast concrete used for slabs, beams, and girders (and in some cases columns as well) is typically prestressed.

In practice, ordinary reinforcing bars are not sufficiently strong to serve as prestressing steel. Prestressing is practical only with extremely high-strength steel strands that are manufactured for the purpose. These are made of cold-drawn steel wires that are formed into small-diameter cables.

Pretensioning

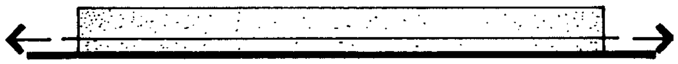
Prestressing is accomplished in two different ways. *Pretensioning* is used with precast concrete members: High-strength steel strands are stretched tightly between abutments in a precasting plant, and the concrete member (or, more commonly, a series of concrete members arranged end to end) is cast around the stretched steel (Figure 15.8). The curing concrete adheres to the strands along their entire length. After the concrete has cured to a specified minimum compressive strength, the strands are cut off at either end of each member. This releases the external tension on the steel, allowing it to recoil slightly, which squeezes all of the concrete of the member into compression. If, as is usually the case, the steel is placed as close as possible to the tension side of the member, the member takes on a decided *camber* (lengthwise arching) at the time the steel strands are cut (Figure 13.37). Much or all of this camber disappears later when the member is subjected to loads in a building.

The strong abutments needed to hold the tensioned strands prior to the pouring of concrete are very expensive to construct except in a single fixed location where many concrete members can be created within the same set of abutments. For this reason, pretensioning is useful only for concrete members cast in precasting plants.

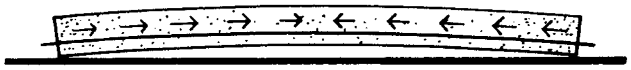
Posttensioning

Unlike pretensioning, which is always done in a factory, *posttensioning* is done almost exclusively in place on the building site. The high-strength steel strands (called *tendons*) are covered with a steel or plastic tube to prevent them from bonding to the concrete and are not tensioned until the concrete has cured. Each tendon is anchored to a steel plate embedded in one end of the beam or slab.

1. *The first step in pretensioning is to stretch the steel prestressing strands tightly across the casting bed*

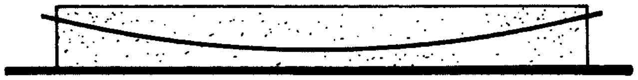


2. *Concrete is cast around the stretched strands and cured. The concrete bonds to the strands*

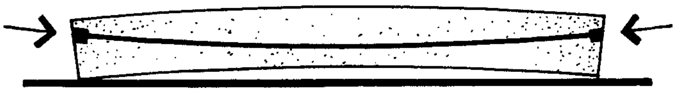


3. *When the strands are cut the concrete goes into compression and the beam takes on a camber*

FIGURE 13.37
Pretensioning. Photographs of pretensioned steel strands for a beam are shown in Chapter 15.



1. *In posttensioning, the concrete is not allowed to bond to the steel strands during curing*



2. *After the concrete has cured, the strands are tensioned with a hydraulic jack and anchored to the ends of the beam. If the strands are draped, as shown here, higher structural efficiency is possible than with straight strands*

FIGURE 13.38
Posttensioning, using draped strands to more nearly approximate the flow path of tensile forces in the beam.

A hydraulic jack is inserted between the other end of the tendon and a similar steel plate in the other end of the member. The jack applies a large tensile force to the tendon while compressing the concrete with an equal but opposite force that is applied through the plate. The stretched tendon is anchored to the plate at the second end of the member before the jack is removed (Figures 13.38–13.40). (For very long members, the tendons are jacked from both ends to be sure that frictional losses in the tubes do not prevent uniform tensioning.)

The net effect of posttensioning is essentially identical to that of pretensioning. The difference is that in posttensioning, abutments are not needed because the member itself provides the abutting force needed to tension the steel. When the posttensioning process is complete, the tendons may be left unbonded, or, if they are in a steel tube, they may be bonded by injecting grout to fill the space between the tendons and the tube. Bonded construction is common in bridges and other heavy structures, but most posttensioning in buildings is done with unbonded tendons. These are made up of seven cold-drawn steel wires and are either 0.5 or 0.6 inch (12.7 or 15.2 mm) in diameter (Figures 13.40 and 13.41). The tendon is coated with a lubricant and covered with a plastic sheath at the factory.

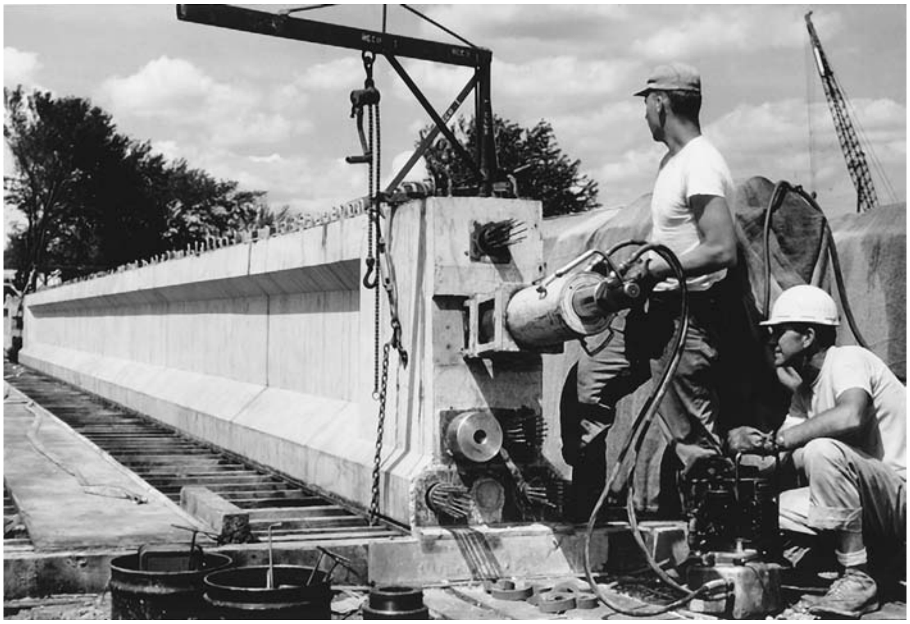
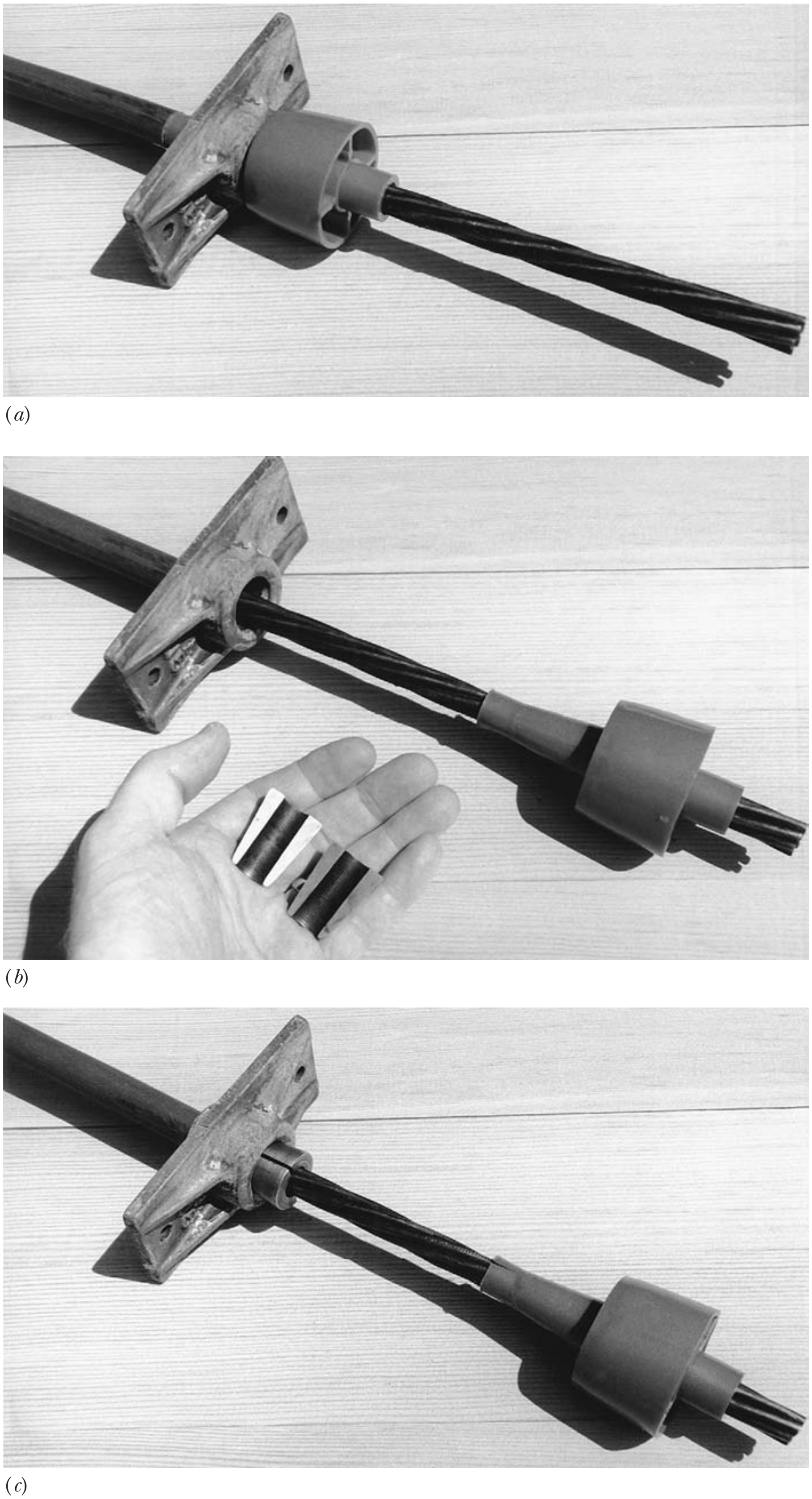


Figure 13.39
Posttensioning draped tendons in a large concrete beam with a hydraulic jack. Each tendon consists of a number of individual high-strength steel strands. The bent bars projecting from the top of the beam will be embedded in the concrete slab that the beam will support to allow them to act together as a composite structure. *(Reprinted with permission of the Portland Cement Association from* Design and Control of Concrete Mixtures, *12th edition; Photos: Portland Cement Association, Skokie, IL)*

Figure 13.40
Most beams and slabs in buildings are posttensioned with plastic-sheathed, unbonded tendons. The pump and hydraulic jack (also called a "ram") are small and portable. *(Courtesy of Constructive Services, Inc., Dedham, Massachusetts)*


(*a*)

(*b*)

(*c*)

Figure 13.41
An end anchorage for small posttensioning tendons is ingeniously simple. (*a*) A steel anchor plate and a plastic pocket former are nailed to the inside of the concrete formwork, with the larger circular face of the pocket former placed against the vertical face of the formwork. The end of the tendon extends through a hole drilled in the formwork. (*b*) After the concrete has cured, the formwork is stripped and the pocket former is retracted, leaving a neat pocket in the edge of the slab for access to the anchor plate, which lies recessed below the surface of the concrete. Two conical wedges with sharp ridges inside are inserted around the tendon and into the conical hole in the anchor plate. (*c*) The ram presses against the wedges and draws the tendon through them until the gauge on the pump indicates that the required tension has been achieved. When the ram is withdrawn, the wedges are drawn into the conical hole, grip the tendon, and maintain the tension. After all the tendons have been tensioned, the excess length of tendon is cut off and the pocket is grouted flush with the edge of the slab. *(Photos by Edward Allen)*

Even higher structural efficiencies are possible in a prestressed beam or slab if the steel strands are placed to follow as closely as possible the lines of tensile force that are diagrammed in Figure 13.26. In a posttensioned beam or slab, this is done by using chairs of varying heights to support the tendons along a curving line that traces the center of the tensile forces in the member. Such a tendon is referred to as being *draped* (Figures 13.38 and 13.39). Draping is impractical in pretensioned members because the tendons would have to be pulled down at many points along their length. But pretensioned strands can be *harped*, that is, pulled up and down in the formwork to make a downward-pointing or flattened V shape in each member that approximates very roughly the shape of a draped tendon (Figure 13.42).

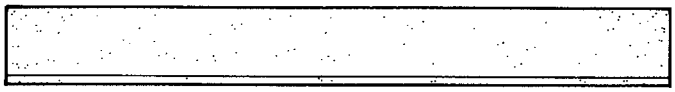
Because it is always highly compressed by prestressing force, the concrete in a prestressed member is subject to long-term progressive shortening (creep). The steel strands also stretch slightly over time and lose some of their prestressing force. Initial prestressing forces must be increased slightly above their theoretically correct values to make up for these long-term movements. Further increases in initial tension are needed to accommodate the slight curing shrinkage that takes place in concrete, small, short-term movements caused by elastic shortening of the concrete during structural loading, and frictional losses and initial slippage or offset of the strand anchors in posttensioned members.

Succeeding chapters will discuss prestressed concrete, both pretensioned and posttensioned, in greater detail, showing its application to various standard precast and cast-in-place systems of construction.

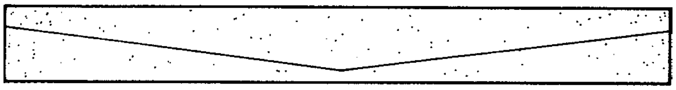
Innovations in Concrete Construction

The basic materials, concrete and steel, are constantly undergoing research and development, leading to higher allowable strengths and decreased weight of structures. Structural lightweight concretes are being used more widely to reduce loads still further. Shrinkage-compensating cements have been developed for use in concrete structures that cannot be allowed to shrink during curing. Self-consolidating concrete is being used to improve productivity and reduce labor costs. Improved coatings for reinforcing steel, steel alloys with greater corrosion resistance, and nonmetallic reinforcing are being used to extend the life of structures exposed to the weather, marine environments, and road salts.

Concretes with compressive strengths as high as 30,000 psi (200 MPa) and exhibiting even usable tensile strength are called *ultra-high performance concretes (UHPCs)*. They are formulated from portland cement, silica fume, silica or quartz flour (extremely finely ground silica or quartz), fine sand, high-range water reducer, water, and steel fibrous reinforcing. There is no large aggregate. The resulting concrete is characterized by a dense packing of the fine aggregate and finely ground mineral powders within the cementitious matrix, resulting in concrete that is stronger, less permeable, and more durable than conventional high-strength mixes. The addition of steel macrofiber reinforcing imparts tensile strength and ductility (toughness). Ultra-high performance concrete can be used in the casting of remarkably thin architectural elements. Precast exterior cladding panels and arched canopies, for example, both no thicker than ¾ inch (20 mm) and with no conventional reinforcing, have been produced from this material (Figures 13.43 and 13.44). Ultra-high performance concrete is suitable for structural applications where very high load capacity, low weight, and high durability are required. By reducing the volume of concrete required in such applications, its use also reduces green house gas emissions resulting from the manufacture of concrete in comparison to the use of conventional, lower-strength concretes.



Straight pretensioning strands



Depressed pretensioning strands

Harped pretensioning strands

FIGURE 13.42
Shaping pretensioning strands to improve structural efficiency. Examples of depressed and harped strands are shown in Chapter 15.

FIGURE 13.43

The Shawnessy LRT Station in Calgary, Alberta, designed by Stantec Architecture, Ltd. The canopy shells were cast from ultra-high-performance concrete and are only ¾ inch (19 mm) thick. *(Courtesy of Lafarge North America, Inc. Photography by Tucker Photography)*

Light transmitting concrete is made from precast concrete blocks or panels with embedded optic fibers or fabrics that allow light to pass through the material while retaining the strength and durability of the concrete. This recently formulated material is finding application in nonstructural partitions, countertops, and other architectural elements.

FIGURE 13.44

Casting of a concrete shell for the Shawnessy LRT Station shown in the previous figure. The shells were injection molded, a technique in which the concrete is cast in a fully enclosed mold rather than in a conventional open-sided form. In this photograph, the two halves of a mold have been separated, and the shell is being lifted with the aid of a temporary frame. *(Courtesy of Lafarge North America, Inc. Photography by Tucker Photography)*

KEY TERMS AND CONCEPTS

- portland cement
- concrete
- aggregate
- coarse aggregate
- fine aggregate
- curing
- hydration
- heat of hydration
- drying shrinkage
- clinker
- air-entraining cement
- white portland cement
- high-volume fly-ash concrete (HVFA concrete)
- lightweight aggregate
- structural lightweight aggregate
- expanded shale aggregate
- vermiculite
- perlite
- supplementary cementitious material (SCM)
- pozzolan
- fly ash
- silica fume, microsilica
- natural pozzolan
- high reactivity metakaolin
- blast furnace slag, slag cement
- hydraulic cement
- blended cement
- concrete admixture
- air-entraining admixture
- water-reducing admixture
- high-range water-reducing admixture, superplasticizer
- accelerating admixture
- retarding admixture
- workability agent
- shrinkage-reducing admixture
- corrosion inhibitor
- freeze protection admixture
- extended set-control admixture
- coloring agent
- water–cement ratio, w-c ratio
- transit-mixed concrete
- slump test
- slurry
- segregation
- dropchute
- consolidation
- self-consolidating concrete (SCC)
- formwork
- form release compound
- precasting
- sitecasting, cast-in-place construction
- reinforced concrete
- steel reinforcing bars
- deformed reinforcing bars
- rebar congestion
- welded wire reinforcing (WWR), welded wire fabric (WWF)
- bottom bar
- cover
- bond
- hook
- stirrup
- U-stirrup
- closed stirrup-tie
- chair
- bolster
- one-way action
- shrinkage–temperature steel
- two-way action
- vertical bar, column bar
- tie
- column tie
- column spiral
- fibrous reinforcing
- microfiber reinforcing
- plastic shrinkage cracking
- macrofiber reinforcing
- creep
- prestress
- prestressed concrete
- pretensioning
- camber
- posttensioning
- tendon
- draped tendon
- harped tendon
- ultra-high performance concrete (UHPC)
- light transmitting concrete
- ACI 301

REVIEW QUESTIONS

1. What is the difference between cement and concrete?

2. List the conditions that must be met to make a satisfactory concrete mix.

3. List the precautions that should be taken to cure concrete properly. How do these change in very hot, very windy, and very cold weather?

4. What problems are likely to occur if concrete has too low a slump? Too high a slump? How can the slump be increased without increasing the water content of the concrete mixture?

5. Explain how steel reinforcing bars work in concrete.

6. Explain the role of stirrups in beams.

7. Explain the role of ties in columns.

8. What does shrinkage-temperature steel do? Where is it used?

9. Explain the differences between reinforcing and prestressing and the relative advantages and disadvantages of each.

10. Under what circumstances would you use pretensioning, and under what circumstances would you use posttensioning?

11. Explain the advantages of using higher strength reinforcing bars in concrete that requires very heavy reinforcing.

EXERCISES

1. Design a simple concrete mixture. Mix it and pour some test cylinders for several water–cement ratios. Cure and test the cylinders. Plot a graph of concrete strength versus water–cement ratio.

2. Sketch from memory the pattern of reinforcing for a continuous concrete beam. Add notes to explain the function of each feature of the reinforcing.

3. Design, form, reinforce, and cast a small concrete beam, perhaps 6 to 12 feet (2–4 m) long. Get help from a teacher or professional, if necessary, in designing the beam.

4. Visit a construction site where concrete work is going on. Examine the forms, reinforcing, and concrete work. Observe how concrete is brought to the site, transported, placed, compacted, and finished. How is the concrete supported after it has been poured? For how long?

14

SITECAST CONCRETE FRAMING SYSTEMS

Boston City Hall makes bold use of sitecast concrete in its structure, facades, and interiors. Its base is faced with brick masonry. *(Architects: Kallmann, McKinnell, and Wood. Photograph: Ezra Stoller © ESTO)*

concrete, helping to prevent curling (warping) of the slab that can occur during curing when the top of the slab loses moisture more rapidly than the bottom. However, this practice also runs the risk of creating a reservoir for the storage of water under the slab that can lead to moisture-related problems after the slab is in service, especially when the slab is covered with floor coverings that are sensitive to moisture, such as resilient sheet flooring or vinyl composition tiles. Particularly with the advent of tougher vapor retarder sheets that are less vulnerable to damage during construction operations, the practice of placing an aggregate layer over the vapor retarder has become less prevalent.

A reinforcing mesh of welded wire reinforcing (also called “welded wire fabric”), cut to a size just a bit smaller than the dimensions of the slab, is laid over the moisture barrier or crushed stone. The reinforcing most commonly used for lightly loaded slabs, such as those in houses, is 6 × 6-W1.4 × W1.4, which has a wire spacing of 6 inches (150 mm) in each direction and a wire diameter of 0.135 inch (3.43 mm—see Figure 13.23 for more information on welded wire fabric). For slabs in factories, warehouses, and airports, a fabric made of heavier wires or a grid of reinforcing bars may be used instead. The grid of wires or bars helps protect the slab against cracking that might be caused by concrete shrinkage, temperature stresses, concentrated loads, frost heaving, or settlement of the ground beneath. Fibrous (macrofiber) reinforcing, discussed in the previous chapter, can also be used in place of wire reinforcing for general crack control in slabs.

(*g*) Floating can be done by machine instead of by hand. (*h*) Steel troweling after floating produces a dense, hard, smooth surface. (*i*) A section of concrete slab on grade finished and ready for curing. The dowels inserted through the edge form will connect to the sections of slab that will be poured next. (*j*) One method of damp curing a slab is to cover it with polyethylene sheet to retain moisture in the concrete. *(Photos a, b, c, and i courtesy of Vulcan Metal Products, Inc., Birmingham, Alabama; photos d, e, f, g, h, and j reprinted with permission of the Portland Cement Association from Design and Control of Concrete Mixtures, 12th edition, Portland Cement Association, Skokie, IL)*

Pouring and Finishing the Slab on Grade

Pouring (casting) of the slab commences with placing concrete in the formwork. This may be done directly from the chute of a transit-mix truck, or with wheelbarrows, concrete buggies, a large crane-mounted concrete bucket, a conveyor belt, or a concrete pump and hoses. The method selected will depend on the scale of the job and the accessibility of the slab to the truck delivering the concrete. The concrete is spread by workers using shovels or rakes until the form is full. Then the same tools are used to agitate the concrete slightly, especially around the edges, to eliminate air pockets. As the concrete is placed, the concrete masons reach into the wet concrete with metal hooks and raise the welded wire fabric to approximately the midheight of the slab, the position in which it is best able to resist tensile forces caused by forces acting either upward or downward on the slab.

The first operation in finishing the slab is to *strike off* or *screed* the concrete by drawing a stiff plank of wood or metal across the top edges of the formwork to achieve a level concrete surface (Figure 14.3*d*). This is done with an end-to-end sawing motion of the plank that avoids tearing the projecting pieces of coarse aggregate from the surface of the wet concrete. A bulge of concrete is maintained in front of the screed as it progresses across the slab, so that when a low point is encountered, concrete from the bulge will flow in to fill it.

Immediately after striking off the concrete, the slab receives its initial *floating*. This step is usually performed by hand, using flat-surfaced tools, typically 4 to 10 feet (1.2 to 3 m) in length, called *bull floats* or *darbies* (Figure 14.3*e*). These are drawn across the concrete to flatten and consolidate its surface. After this initial floating, the top of the slab is level but still rather rough. If a concrete topping will later be poured over the slab, or if a floor finish of terrazzo, stone, brick, or quarry tile will be applied, the slab may be left to cure without further finishing.

If a smoother surface is desired, additional finishing operations proceed after a period of time during which the concrete begins to stiffen and the watery sheen, called *bleed water*, evaporates from the surface of the slab. First, specially shaped hand tools may be used to form neatly rounded edges around the perimeter of the slab and control joints in the interior. Next, the slab is floated a second time to further consolidate its surface. At this stage, small slabs may be floated by hand (Figure 14.3*f*), but for larger slabs, rotary power floats are used (Figure 14.3*g*). The working surfaces of floats are made of wood or of metal with a slightly rough surface. As the float is drawn across the surface, the friction generated by this roughness vibrates the concrete gently and brings cement paste to the surface, where it is smoothed over the coarse aggregate and into low spots by the float. If too much floating is done, however, an excess of paste and free water rises to the surface and forms puddles, making it almost impossible to get a good finish. Experience on the part of the mason is essential to floating, as it is to all slab finishing operations, to know just when to begin each operation and just when to stop. The floated slab has a lightly textured surface that is appropriate for outdoor walks and pavings without further finishing.

For a completely smooth, dense surface, the slab must also be *troweled*.

Controlling Cracking in Concrete Slabs on Grade

Because concrete slabs on grade are relatively thin in relation to their horizontal dimensions and usually are relatively lightly reinforced, they are particularly prone to cracking. The stresses that cause cracking may originate from the shrinkage that is a normal part of the concrete curing process, from thermal expansion and contraction of the slab, or from differential movement between the slab and abutting building elements. If such cracks are allowed to occur randomly, they can be unsightly and can compromise the functionality of the slab.

Most commonly, cracking in concrete slabs on grade is managed by introducing an organized system of joints into the slab that allow stresses to be relieved without compromising the appearance or performance of the slab. *Control joints*, also called *contraction joints*, are intentionally weakened sections through a concrete slab where the tensile forces caused by concrete drying shrinkage can be relieved without disfiguring the slab. They are usually formed as grooves that extend at least one-quarter of the depth of the slab, created either by running a special trowel along a straightedge while the concrete is still plastic or by sawing partially through the concrete shortly after it begins to harden using a diamond or abrasive saw blade in a power circular saw. To provide a further inducement for cracks to occur at control joint locations rather than elsewhere in the slab, reinforcing in the slab may be partially discontinued where it crosses these joints. Control joint spacing recommendations vary with the thickness of the slab and the shrinkage rate of the concrete. For example, for slabs 4 to 8 inches (100 200 mm) thick made with ordinary concrete, joints spacings from 11 feet 6 inches to 17 feet 6 inches (3.6 5.3 m) are recommended (the thinner the slab, the closer the joint spacing) Where control joints run in perpendicular directions, they should be spaced more or less equally in each direction to create panels that are square or close to square in proportion.

> **Reinforced concrete made "pilotis" possible. The house is in the air, away from the ground; the garden runs under the house, and it is also above the house, on the roof. . . . Reinforced concrete is the means which makes it possible to build all of one material. . . . Reinforced concrete brings the free plan into the house! Floors no longer have to stand simply one on top of the other. They are free. . . . Reinforced concrete revolutionizes the history of the window. Windows can run from one end of the facade to the other . . .**
>
> **Le Corbusier and P. Jeanneret, *Oeuvre Complète 1910–1929,* 1956.**

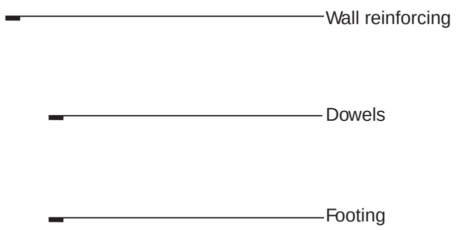
Isolation joints, sometimes also called *expansion joints*, are formed by casting full-depth preformed joint materials, typically ⅜ to ¾ inch (10 20 mm) in width, into the slab (Figure 14.3*c*), completely separating the slab from adjacent elements. Isolation joints relieve potential stresses by allowing freedom of movement of the slab with respect to other building parts or other portions of the slab movements that may occur due to thermal expansion and contraction, structural loading, or differential settlement. Isolation joints are commonly provided where the edge of a concrete slab abuts adjacent walls or curbs, as well as around elements, such as columns or loadbearing walls, which pass through the slab within its perimeter. Isolation joints are also used to divide large or irregularly shaped slabs into smaller, more simply shaped rectangular areas that are less prone to stress accumulation.

Concrete itself can be manipulated to reduce cracking: Shrinkage-reducing chemical admixtures and some supplementary cementitious materials, such as fly ash, reduce drying shrinkage. Lowering the water cement ratio of the concrete mix both reduces drying shrinkage and results in finished concrete that is stronger and more crack resistant. Specially formulated *shrinkage-compensating cements* can completely nullify drying shrinkage, allowing the casting of large slabs on grade entirely free of contraction joints. The amount of steel reinforcing in the slab can be increased or fibrous reinforcing can be added to the concrete mix to improve a concrete slab s resistance to tensile forces. Protecting a freshly poured concrete slab from premature drying during the damp curing process reduces cracking while the concrete hardens and ensures that the concrete attains its full design strength.

Under certain circumstances, it is advantageous to posttension a slab on grade, using level tendons in both directions at the midheight of the slab rather than welded wire fabric. Posttensioning places the entire slab under sufficient compressive stress so that it will never experience tensile stress under any anticipated conditions. Posttensioning makes floors resistant to cracking under concentrated loads, eliminates the need to make control joints, and often permits the use of a thinner slab. It is especially effective for slabs over unstable or inconsistent soils and for superflat floors.

CASTING A CONCRETE WALL

A reinforced concrete wall at ground level usually rests on a poured concrete strip footing (Figures 14.5–14.7). The footing is formed and poured much like a concrete slab on grade. Its cross-sectional dimensions and its reinforcing, if any, are determined by the structural engineer. A *key*, a groove that will form a mechanical connection to the wall, is sometimes formed in the top of the footing with strips of wood that are temporarily embedded in the wet concrete. Vertically projecting *dowels* of steel reinforcing bars are usually installed in the footing before pouring; these will later be overlapped with the vertical bars in the walls to form a strong structural connection. After pouring, the top of the footing is screeded; no further finishing operations are required. The footing is left to cure for at least a day before the wall forms are erected.



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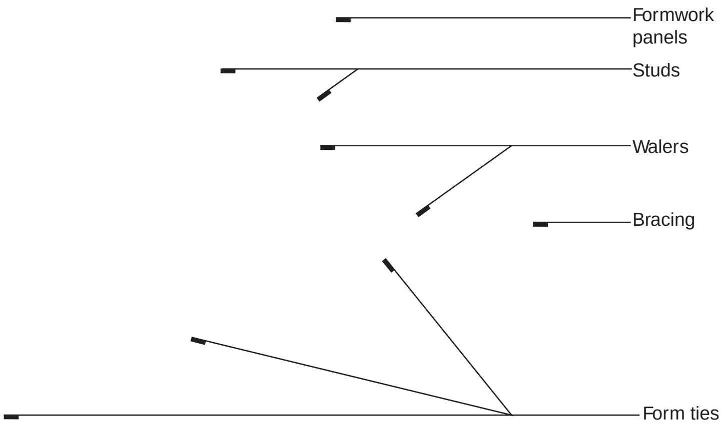


(*b*)

(*c*)

FIGURE 14.5
The process of casting a concrete wall. (*a*) Vertical reinforcing bars are wired to the dowels that project from the footing, and horizontal bars are wired to the vertical bars. (*b*) The formwork is erected. Sheets of plywood form the faces of the concrete. They are supported by vertical wood studs. The studs are supported against the pressure of the wet concrete by horizontal walers. The walers are supported by steel rod ties that pass through holes in the plywood to the walers on the other side. The ties also act as spreaders to maintain a spacing between the plywood walls that is equal to the desired thickness of the wall. Diagonal braces keep the whole assembly plumb and straight. (*c*) After the concrete has been poured, consolidated, and cured, the wedges that secure the walers to the form ties are driven out and the formwork is pulled off the concrete. The projecting ends of the form ties are broken off.

Figure 14.8
Detail of a form tie assembly. Two plastic cones just inside the faces of the form maintain the correct wall thickness. Tapered, slotted wedges at the ends transmit force from the tie to the walers. After the forms have been stripped, the cones will be removed from the concrete and the ties snapped off inside the voids left by the cones. The conical holes may be left open, filled with mortar, or plugged with conical plastic plugs.

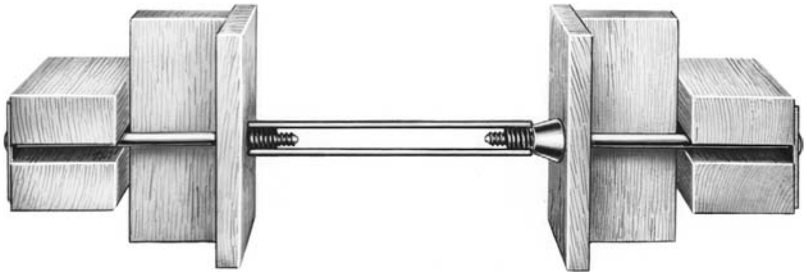
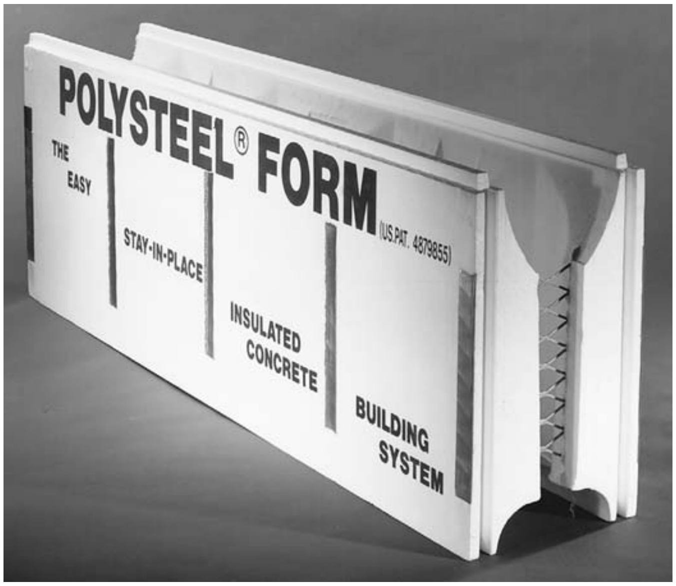


Figure 14.9
Detail of a heavy-duty form tie. This assembly is tightened with special screws that engage a helix of heavy wire welded into the tie. The wire components remain in the concrete, but the screws and the plastic cone on the right are removed and reused after stripping. The purpose of the cone is to give a neatly finished hole in the exposed surface of the concrete. *(Courtesy of Richmond Screw Anchor Co., Inc., 7214 Burns St., Fort Worth, TX 76118)*

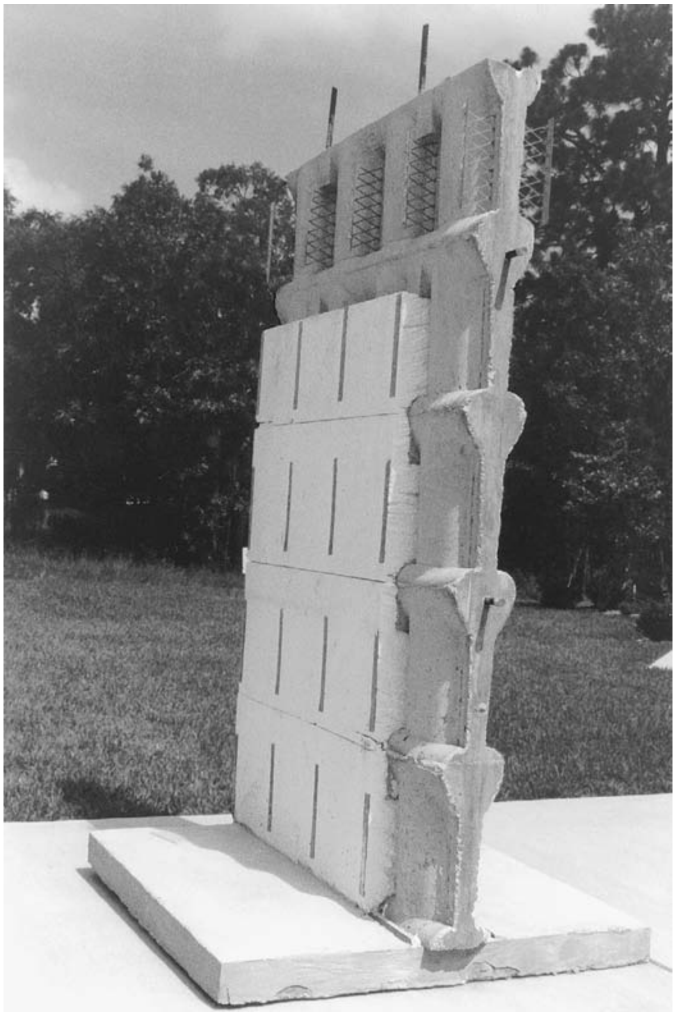
Figure 14.10
Consolidating wet concrete after pouring, using a mechanical vibrator immersed in the concrete. *(Reprinted with permission of the Portland Cement Association from* Design and Control of Concrete Mixtures, *12th edition; Photos: Portland Cement Association, Skokie, IL)*



(*a*)

FIGURE 14.12
Forming a concrete wall with insulating concrete forms. (*a*) The forms are manufactured as interlocking blocks. The inner and outer halves of the blocks are tied together by steel mesh webs that connect to sheet metal strips on the inner and outer surfaces. These strips later serve to receive screws that fasten interior and exterior finish materials to the wall. (*b*) Workers stack the blocks to form all the exterior walls of a house. Openings for doors and windows are formed with dimension lumber. The worker to the right is cutting a formwork block to length with a hand saw. (*c*) This sample wall, from which some of the blocks have been removed, shows that the completed wall contains a continuous core of reinforced concrete with thermal insulation inside and out. *(Courtesy of American Polysteel Forms)*

(*b*)



(*c*)

Insulating Concrete Forms

An alternative way of casting a concrete wall, particularly one that will be an exterior wall of a building, is to use *insulating concrete forms (ICFs)* that serve both to form the concrete and to remain in place permanently as thermal insulation (Figure 14.12). The forms are manufactured in slightly differing configurations by dozens of companies. The most common form is interlocking hollow blocks of polystyrene foam, but some manufacturers produce planks or panels of foam with plastic ties that join them to make wall forms. Whatever the exact configuration, these systems weigh so little and are so accurately made that they go together almost as easily and quickly as a child's plastic building blocks. The tops of the blocks are channeled in such a way that horizontal reinforcing bars may be laid in the top of each course and vertical bars may be inserted into the vertical cores. The wall forms must be braced strongly to prevent them from moving during pouring. Concrete is usually deposited in the cores of the foam blocks from the hose of a concrete pump. The full height of a wall cannot be cast in one operation because the pressure of so great a depth of wet concrete would blow out the sides of the fragile blocks. The normal procedure is to deposit the concrete in several "lifts" of limited height, working all the way around the structure with each lift so that by the time the second lift is begun, the first lift has had an hour or two to harden somewhat, relieving the pressure at the bottom of the forms. Interior and exterior finish materials must be applied to the foam plastic faces to protect them from sunlight, mechanical damage, and fire. The thermal insulating value of the finished wall is usually R17 to R22, which is generally sufficient to meet current code requirements.

CASTING A CONCRETE COLUMN

A column is formed and cast much like a wall, with a few important differences. The footing is usually an isolated column footing, a pile cap, or a caisson rather than a strip footing (Figure 14.13). The dowels are sized and spaced in the footing to match the vertical bars in the column. The cage of column reinforcing is assembled with wire ties and hoisted into place over the dowels. If space is too tight in the region where the vertical

(*a*)

(*b*)

FIGURE 14.13
(*a*) A column footing almost ready for pouring but lacking dowels. The reinforcing bars are supported on pieces of concrete brick. (*b*) Column footings poured with projecting dowels to connect to both round and rectangular columns. *(Photos by Edward Allen)*

Figure 14.42

Banded tendons run directly through the concrete column of this flat plate floor. A substantial amount of conventional reinforcing is used here for shear reinforcing. Notice the end anchorage plates nailed to the vertical surface of the formwork at the upper right; see also Figure 13.40. (*Courtesy of Post-Tensioning Institute*)

Selecting a Sitecast Concrete Framing System

Preliminary factors to be considered in the selection of a sitecast concrete framing system for a building include the following (Figures 14.43 and 14.44):

1. Are the bays of the building square or nearly square? If so, a two-way system will probably be more economical than a one-way system.

2. How long are the spans? Spans up to 25 or 30 feet (7.6 or 9.1 m) are usually accomplished most economically with a two-way flat plate or flat slab system because of the relative simplicity of the formwork. For longer spans, a one-way joist system may be a good choice. Posttensioning extends significantly the economical span range of any of these systems.

3. How heavy are the loads? Heavy industrial loadings are borne better by thicker slabs and larger beams than they are by light joist construction. Ordinary commercial, institutional, and residential loadings are carried easily by flat plate or joist systems.

4. Will there be a finish ceiling beneath the slab? If not, flat plate and one-way slab construction have smooth, paintable undersides that can serve as ceilings.

5. Does the lateral stability of the building against wind and seismic loads have to be provided by the rigidity of the concrete frame? Flat plate floors may not be sufficiently rigid for this purpose, which would favor a one-way system with its deeper beam-to-column connections.

Innovations in Sitecast Concrete Construction

The development of sitecast concrete construction continues along several lines. The basic materials, concrete and steel, continue to undergo innovations, as described in Chapter 13. The continuing evolution of high-strength, high-stiffness concrete, along with improvements in concrete forming systems and concrete pumping technology, have enabled sitecast concrete construction to remain economically competitive with structural steel for buildings of virtually any type or size. The world's tallest building at the time of this writing, the Burj Dubai, in Dubai, United Arab Emirates, is being constructed for most of its height as a steel-reinforced sitecast concrete structure.

Formwork generally accounts for more than half the cost of sitecast concrete construction. Efforts to reduce this cost have led to many innovations, including new types of formwork panels that are especially smooth, durable, and easy to clean after they have been stripped. These can be reused dozens of times before they wear out.

For Preliminary Design of a Sitecast Concrete Structure

- Estimate the depth of a **one-way solid slab** at 1/22 of its span if it is conventionally reinforced or 1/40 of its span if it is posttensioned. Depths range typically from 4 to 10 inches (100–250 mm).
- Estimate the total depth of a **one-way concrete joist system** or **wide-module system** at 1/18 of its span if it is conventionally reinforced or 1/36 of its span if it is posttensioned. For standard sizes of the pans used to form these systems, see Figure 14.23. To arrive at the total depth, a slab thickness of 3 to 4½ inches (75–115 mm) must be added to the depth of the pan that is selected.
- Estimate the depth of **concrete beams** at 1/16 of their span if they are conventionally reinforced or 1/24 of their span if they are posttensioned. For concrete girders, use ratios of 1/12 and 1/20, respectively.
- Estimate the depth of **two-way flat plates** and **flat slabs** at 1/30 of their span if they are conventionally reinforced or 1/45 of their span if they are posttensioned. Typical depths are 5 to 12 inches (125–305 mm). The minimum column size for a flat plate is approximately twice the depth of the slab. The width of a drop panel for a flat slab is usually one-third of the span, and the projection of the drop panel below the slab is about one-half the thickness of the slab.
- Estimate the depth of a **waffle slab** at 1/24 of its span if it is conventionally reinforced or 1/35 of its span if it is posttensioned. For standard sizes of the domes used to form waffle slabs, see Figure 14.35. To arrive at the total depth, a slab thickness of 3 to 4½ inches (75–115 mm) must be added to the depth of the dome that is selected.
- To estimate the size of a **concrete column** of normal height, add up the total roof and floor area supported by the column. A 12-inch (300-mm) column can support up to about 2000 square feet (190 m^2) of area, a 16-inch (400-mm) column 4000 square feet (370 m^2), a 20-inch (500-mm) column 6000 square feet (560 m^2), a 24-inch (600-mm) column 9000 square feet (840 m^2), and a 28-inch (700-mm) column 10,500 square feet (980 m^2). These sizes are greatly influenced by the strength of the concrete used and the ratio of reinforcing steel to concrete. Columns are usually round or square.
- To estimate the thickness of a **concrete loadbearing wall**, add up the total width of floor and roof slabs that contribute load to the wall. An 8-inch (200-mm) wall can support approximately 1200 feet (370 m) of slab, a 10-inch (250-mm) wall 1500 feet (460 m), a 12-inch (300-mm) wall 1700 feet (520 m), and a 16-inch (400-mm) wall 2200 feet (670 m). These thicknesses are greatly influenced by the strength of the concrete used and the ratio of reinforcing steel to concrete.

These approximations are valid only for purposes of preliminary building layout and must not be used to select final member sizes. They apply to the normal range of building occupancies, such as residential, office, commercial, and institutional buildings, and parking garages. For manufacturing and storage buildings, use somewhat larger members.

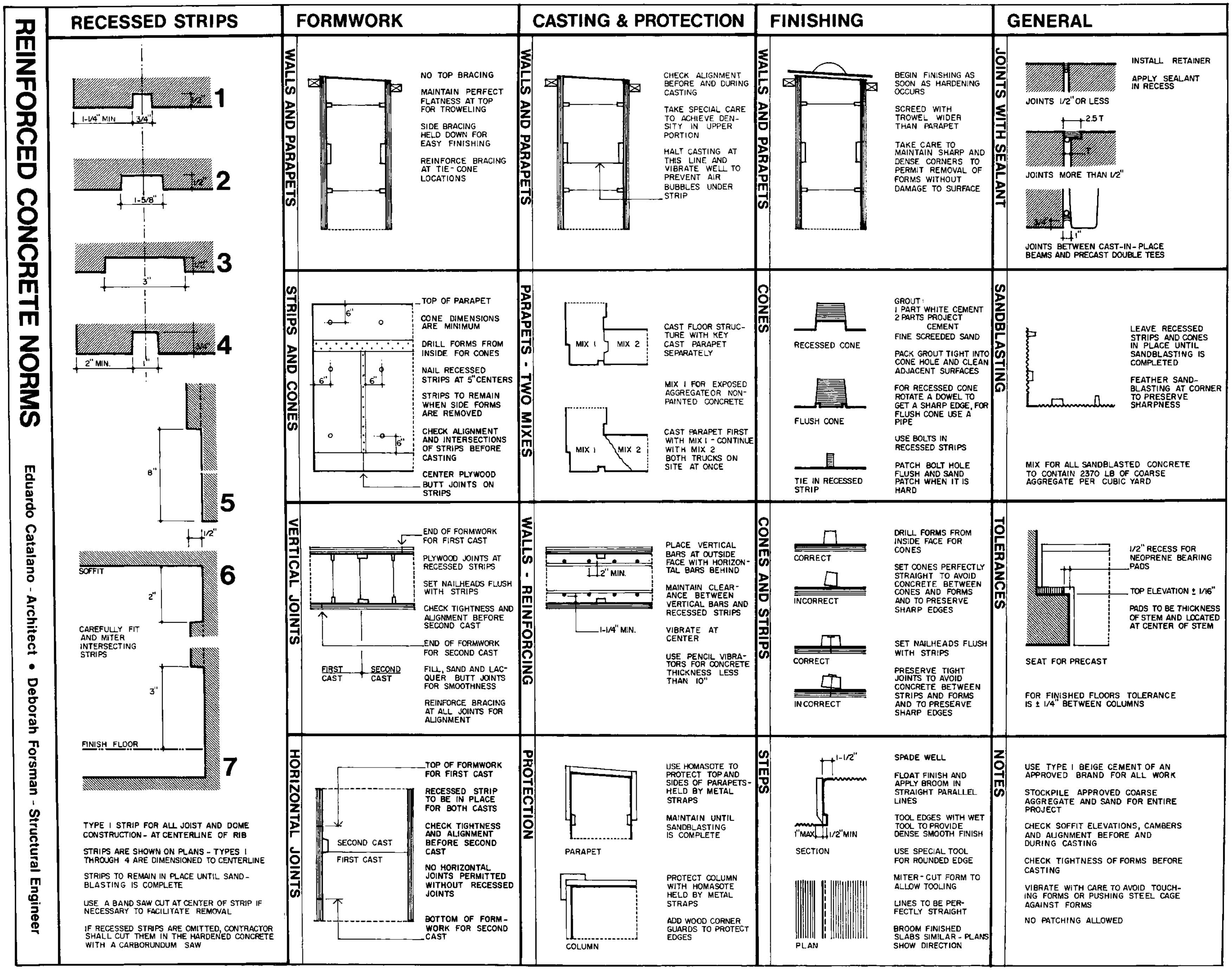
For more comprehensive information on preliminary selection and layout of a structural system and sizing of structural members, see Edward Allen and Joseph Iano, *The Architect's Studio Companion* (4th ed.), Hoboken, John Wiley & Sons, Inc., 2007.

Lift-slab construction, used chiefly with two-way flat plate structures, virtually eliminates formwork. The floor and roof slabs of a building are cast in a stack on the ground. Then hydraulic jacks are used to lift the slabs up the columns to their final elevations, where they are welded in place using special cast-in-place steel slab collars (Figure 14.45).

Ganged forms for wall construction are large units made up of a number of panels that are supported by the same set of walers. These are handled by cranes and are often more economical than conventional small panels that are maneuvered by hand. For floor slabs that are cast in place, *flying formwork* is fabricated in large sections that are supported on deep metal trusses. The sections are moved from one floor to the next by crane, eliminating much of the labor usually expended on stripping and reerecting formwork (Figure 14.46).

Slip forming is useful for tall-walled structures such as elevator shafts, stairwells, and storage silos. A ring of formwork is pulled steadily upward by jacks supported on the vertical reinforcing bars, while workers add concrete and horizontal reinforcing in a continuous process. Manufacturers of concrete formwork have developed more sophisticated systems of self-climbing formwork that offer many advantages over conventional slip forming (Figures 14.19 and 14.47).

In *tilt-up construction* (Figure 14.48), a floor slab is cast on the ground and reinforced concrete wall panels are poured over it in a horizontal position. When curing is complete, the panels are tilted up into a vertical orientation and hoisted into position by a crane, then grouted together. The elimination of most of the usual wall formwork results in formwork costs that are typically less than 5 percent of the cost of the overall concrete system, making tilt-up construction often economical for single-story buildings. Although most tilt-up



REINFORCED CONCRETE NORMS

Eduardo Catalano - Architect • Deborah Forsman - Structural Engineer

RECESSED STRIPS

CAREFULLY FIT AND MITER INTERSECTING STRIPS

TYPE 1 STRIP FOR ALL JOIST AND DOME CONSTRUCTION - AT CENTERLINE OF RIB

STRIPS ARE SHOWN ON PLANS - TYPES 1 THROUGH 4 ARE DIMENSIONED TO CENTERLINE

STRIPS TO REMAIN IN PLACE UNTIL SAND-BLASTING IS COMPLETE

USE A BAND SAW CUT AT CENTER OF STRIP IF NECESSARY TO FACILITATE REMOVAL

IF RECESSED STRIPS ARE OMITTED, CONTRACTOR SHALL CUT THEM IN THE HARDENED CONCRETE WITH A CARBORUNDUM SAW

FORMWORK

WALLS AND PARAPETS

NO TOP BRACING

MAINTAIN PERFECT FLATNESS AT TOP FOR TROWELING

SIDE BRACING HELD DOWN FOR EASY FINISHING

REINFORCE BRACING AT TIE-CONE LOCATIONS

STRIPS AND CONES

TOP OF PARAPET

CONE DIMENSIONS ARE MINIMUM

DRILL FORMS FROM INSIDE FOR CONES

NAIL RECESSED STRIPS AT 5" CENTERS

STRIPS TO REMAIN WHEN SIDE FORMS ARE REMOVED

CHECK ALIGNMENT AND INTERSECTIONS OF STRIPS BEFORE CASTING

CENTER PLYWOOD BUTT JOINTS ON STRIPS

VERTICAL JOINTS

END OF FORMWORK FOR FIRST CAST

PLYWOOD JOINTS AT RECESSED STRIPS

SET NAILHEADS FLUSH WITH STRIPS

CHECK TIGHTNESS AND ALIGNMENT BEFORE SECOND CAST

END OF FORMWORK FOR SECOND CAST

FILL, SAND AND LACQUER BUTT JOINTS FOR SMOOTHNESS

REINFORCE BRACING AT ALL JOINTS FOR ALIGNMENT

HORIZONTAL JOINTS

TOP OF FORMWORK FOR FIRST CAST

RECESSED STRIP TO BE IN PLACE FOR BOTH CASTS

CHECK TIGHTNESS AND ALIGNMENT BEFORE SECOND CAST

NO HORIZONTAL JOINTS PERMITTED WITHOUT RECESSED JOINTS

BOTTOM OF FORMWORK FOR SECOND CAST

CASTING & PROTECTION

WALLS AND PARAPETS

CHECK ALIGNMENT BEFORE AND DURING CASTING

TAKE SPECIAL CARE TO ACHIEVE DENSITY IN UPPER PORTION

HALT CASTING AT THIS LINE AND VIBRATE WELL TO PREVENT AIR BUBBLES UNDER STRIP

PARAPETS - TWO MIXES

CAST FLOOR STRUCTURE WITH KEY CAST PARAPET SEPARATELY

MIX 1 FOR EXPOSED AGGREGATE OR NON-PAINTED CONCRETE

CAST PARAPET FIRST WITH MIX 1 - CONTINUE WITH MIX 2 BOTH TRUCKS ON SITE AT ONCE

WALLS - REINFORCING

PLACE VERTICAL BARS AT OUTSIDE FACE WITH HORIZONTAL BARS BEHIND

MAINTAIN CLEARANCE BETWEEN VERTICAL BARS AND RECESSED STRIPS

VIBRATE AT CENTER

USE PENCIL VIBRATORS FOR CONCRETE THICKNESS LESS THAN 10"

PROTECTION

USE HOMASOTE TO PROTECT TOP AND SIDES OF PARAPETS - HELD BY METAL STRAPS

MAINTAIN UNTIL SANDBLASTING IS COMPLETE

PROTECT COLUMN WITH HOMASOTE HELD BY METAL STRAPS

ADD WOOD CORNER GUARDS TO PROTECT EDGES

FINISHING

WALLS AND PARAPETS

BEGIN FINISHING AS SOON AS HARDENING OCCURS

SCREED WITH TROWEL WIDER THAN PARAPET

TAKE CARE TO MAINTAIN SHARP AND DENSE CORNERS TO PERMIT REMOVAL OF FORMS WITHOUT DAMAGE TO SURFACE

CONES

GROUT:
1 PART WHITE CEMENT
2 PARTS PROJECT CEMENT

FINE SCREEDED SAND

PACK GROUT TIGHT INTO CONE HOLE AND CLEAN ADJACENT SURFACES

FOR RECESSED CONE ROTATE A DOWEL TO GET A SHARP EDGE, FOR FLUSH CONE USE A PIPE

USE BOLTS IN RECESSED STRIPS

PATCH BOLT HOLE FLUSH AND SAND PATCH WHEN IT IS HARD

CONES AND STRIPS

DRILL FORMS FROM INSIDE FACE FOR CONES

SET CONES PERFECTLY STRAIGHT TO AVOID CONCRETE BETWEEN CONES AND FORMS AND TO PRESERVE SHARP EDGES

SET NAILHEADS FLUSH WITH STRIPS

PRESERVE TIGHT JOINTS TO AVOID CONCRETE BETWEEN STRIPS AND FORMS AND TO PRESERVE SHARP EDGES

STEPS

SPADE WELL

FLOAT FINISH AND APPLY BROOM IN STRAIGHT PARALLEL LINES

TOOL EDGES WITH WET TOOL TO PROVIDE DENSE SMOOTH FINISH

USE SPECIAL TOOL FOR ROUNDED EDGE

MITER-CUT FORM TO ALLOW TOOLING

LINES TO BE PERFECTLY STRAIGHT

BROOM FINISHED SLABS SIMILAR - PLANS SHOW DIRECTION

GENERAL

JOINTS WITH SEALANT

INSTALL RETAINER

APPLY SEALANT IN RECESS

JOINTS 1/2" OR LESS

JOINTS MORE THAN 1/2"

JOINTS BETWEEN CAST-IN-PLACE BEAMS AND PRECAST DOUBLE TEES

SANDBLASTING

LEAVE RECESSED STRIPS AND CONES IN PLACE UNTIL SANDBLASTING IS COMPLETED

FEATHER SANDBLASTING AT CORNER TO PRESERVE SHARPNESS

MIX FOR ALL SANDBLASTED CONCRETE TO CONTAIN 2370 LB OF COARSE AGGREGATE PER CUBIC YARD

TOLERANCES

1/2" RECESS FOR NEOPRENE BEARING PADS

TOP ELEVATION ± 1/16"

PADS TO BE THICKNESS OF STEM AND LOCATED AT CENTER OF STEM

SEAT FOR PRECAST

FOR FINISHED FLOORS TOLERANCE IS ± 1/4" BETWEEN COLUMNS

NOTES

USE TYPE 1 BEIGE CEMENT OF AN APPROVED BRAND FOR ALL WORK

STOCKPILE APPROVED COARSE AGGREGATE AND SAND FOR ENTIRE PROJECT

CHECK SOFFIT ELEVATIONS, CAMBERS AND ALIGNMENT BEFORE AND DURING CASTING

CHECK TIGHTNESS OF FORMS BEFORE CASTING

VIBRATE WITH CARE TO AVOID TOUCHING FORMS OR PUSHING STEEL CAGE AGAINST FORMS

NO PATCHING ALLOWED

CUTTING CONCRETE, STONE, AND MASONRY

It is often necessary to cut hard materials, both in the course of obtaining and processing construction materials and during the construction process itself. The quarrying and milling of stone require many cutting operations. Precast concrete elements are frequently cut to length in the factory. Masonry units often need to be cut on the construction site, and masonry walls sometimes require the cutting of fastener holes and utility openings. Concrete cutting has become an industry in itself because of the need for utility openings, fastener holes, control joints, and surface grinding and texturing. Cutting and drilling are required to create new openings and remove unwanted construction during the renovation of masonry and concrete buildings. Core drilling is used to obtain laboratory test specimens of concrete, masonry, and stone. Finally, cutting is sometimes necessary to remove incorrect work and to perform building demolition operations.

In preindustrial times, hard materials were cut with hand tools, such as steel saws that employed an abrasive slurry of sand and water beneath the blade, and hardened steel drills and chisels that were driven with a heavy hammer. Wedges and explosives in drilled holes were used to split off large blocks of material. These techniques and mechanized variations of them are still used to some extent, but diamond cutting tools are rapidly taking over the bulk of the tough cutting chores in the construction industry. Diamond tools are expensive in first cost, but they cut much more rapidly than other types of tools, they cut more cleanly, and they last much longer, so they are usually more economical overall. Furthermore, diamond tools can sometimes do things that conventional tools cannot, such as precision sawing marble and granite into very thin sheets for floor and wall facings.

Diamonds cut hard materials efficiently because they are the hardest known material. Most of the industrial diamonds that go into cutting tools are synthetic. They are produced by subjecting graphite and a catalyst to extreme heat and pressure, then sorting and grading the small diamonds that result. Although some natural diamonds are still used in industry, synthetic diamonds are preferred for most tasks because of their more consistent behavior in use.

To manufacture a cutting tool, the diamonds are first embedded in a metallic bonding matrix and the mixture is formed into small cutting segments. The choice of diamonds and the exact composition of the bonding matrix are governed by the type of material that is to be cut. The cutting segments are brazed to steel cutting tools—circular saw blades, gangsaw blades, core drill cylinders—and the cutting tools are mounted in the machines that drive them. Some tools are designed to cut dry, but most are used with a spray of water that cools the blade and washes away the cut material. The accompanying illustrations (Figures A–J) show a variety of machines that use diamond cutting tools. Another example is shown in Figure 9.25. Diamonds are also made into grinding wheels, which are used for everything from sharpening tungsten carbide tools to flattening out-of-level concrete floors and polishing granite.

Cutting tools based on materials other than diamonds are still common on the construction job site. Tungsten carbide is used for the tips of small-diameter masonry and concrete drills and for the teeth of woodworking saws.

(Continues)

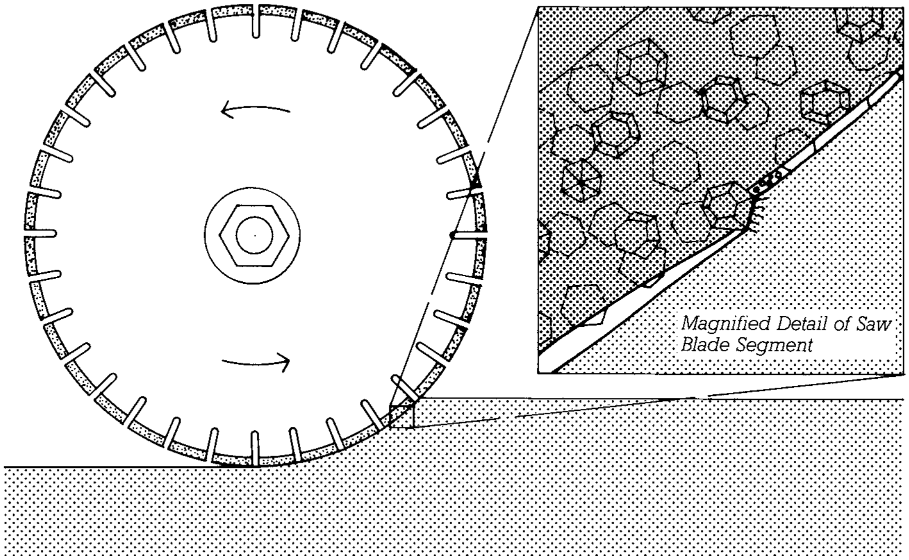


FIGURE A
A *diamond saw* blade is made up of cutting segments brazed to a steel blade core. Each cutting segment consists of diamond crystals embedded in a metallic bonding matrix. The diamonds in the cutting segment fracture chips from the material being cut. In doing so, each diamond gradually becomes chipped and worn and finally falls out of the bonding matrix altogether. The bonding matrix wears at a corresponding rate, exposing new diamonds to take over for those that have fallen out.

CUTTING CONCRETE, STONE, AND MASONRY *(CONTINUED)*

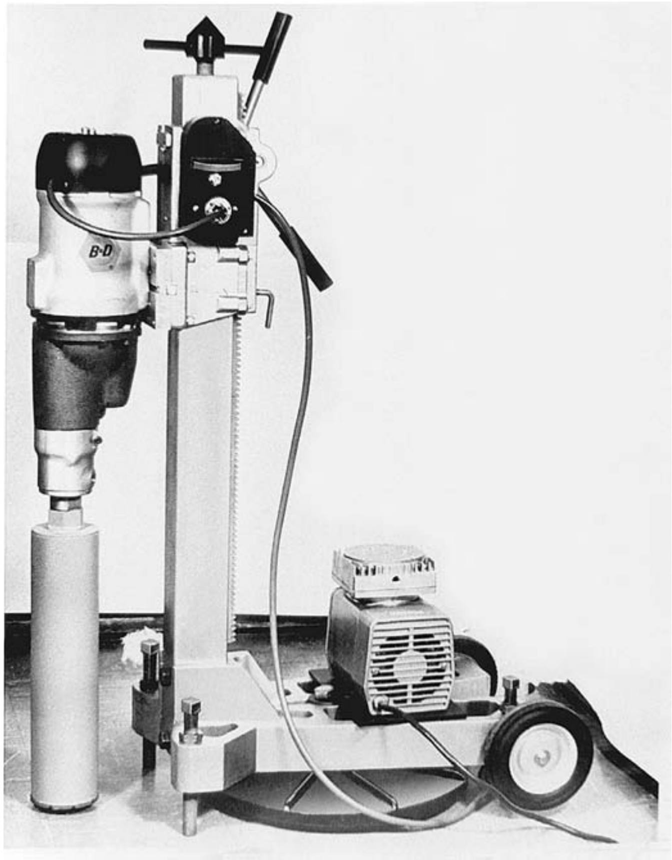


FIGURE G
A diamond core drill is used for cutting round holes. *(Photo courtesy of Sprague & Henwood, Inc., Scranton, Pennsylvania)*

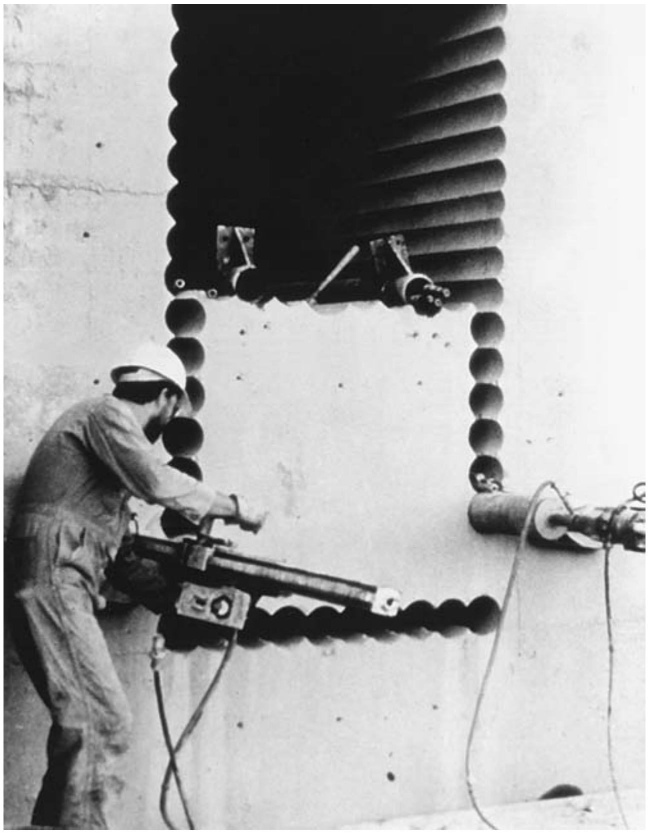


FIGURE H
Using a technique called "stitch drilling," a core drill cuts an opening in a very thick wall. *(Courtesy of GE Superabrasives)*

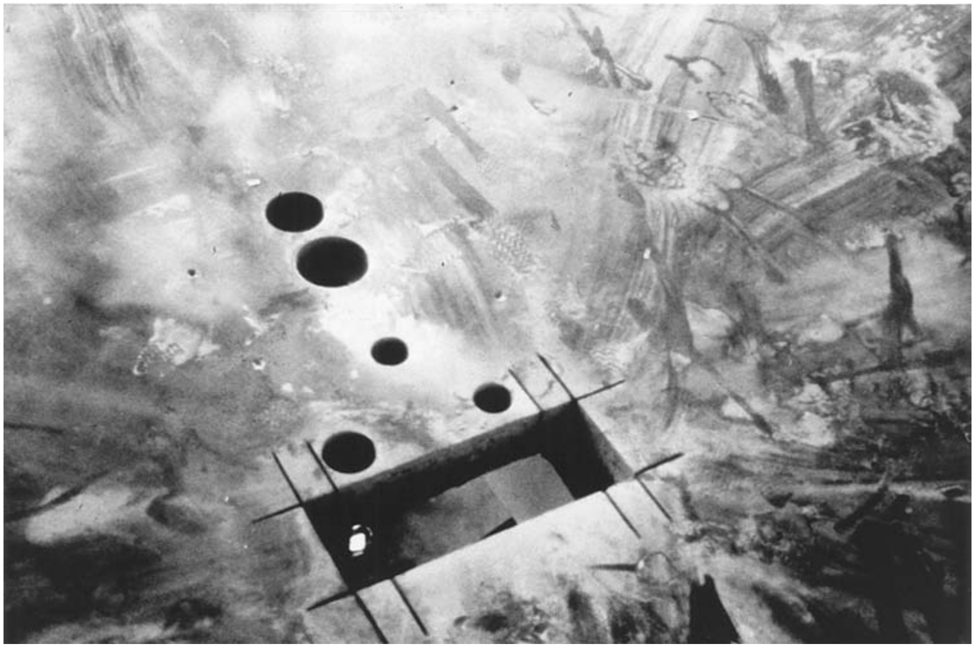


FIGURE I
Sawed and drilled openings for utility lines in a concrete floor slab. *(Courtesy of GE Superabrasives)*

Figure 14.56
Flying formwork is removed from a bay of a folded plate concrete roof for an air terminal. *(Architects: Thorshov and Cerny. Photo courtesy of APA–The Engineered Wood Association)*

on reinforcing or posttensioning to resist the tensile forces that it may experience.

Designing Economical Sitecast Concrete Buildings

The cost of a concrete building frame can be broken down into the costs of the concrete, the reinforcing steel, and the formwork. Of the three, the cost of concrete is usually the least significant in North America and the cost of formwork is the most significant. Accordingly, simplification and standardization of formwork are the first requirements for an economical concrete frame. Repetitive, identical column spacings and bay sizes allow the same formwork to be used again and again without alterations. Flat plate construction is often the most economical, simply because its formwork is so straightforward. Joist band construction is usually more economical than joist construction that uses beams proportioned more efficiently for their structural requirements, because enough is saved on formwork costs to more than compensate for the added concrete and reinforcing steel in the beams. This same reasoning applies if column and beam dimensions are standardized throughout the building, even though loads may vary; the amount of reinforcing and the strengths of the concrete and reinforcing steel can be changed to meet the varying structural requirements (Figure 14.57).

Sitecast Concrete and the Building Codes

Concrete structures are inherently fire resistant. When fire attacks concrete, the water of hydration is gradually driven out and the concrete loses strength, but this deterioration is slow because considerable heat is needed to raise the temperature of the mass of concrete to the point where dehydration begins, and a large additional quantity of heat is required to vaporize the water. The steel reinforcing bars or prestressing strands are buried beneath a concrete cover that protects them for an extended period of time. Except under unusual circumstances, such as a prolonged fire fueled by stored

FIGURE 14.58
Concrete work nears the 1475-foot (450-m) summit of, at the time of their construction, the world's tallest buildings, the twin Petronas Towers in Kuala Lumpur, Malaysia. Each tower is supported by a perimeter ring of 16 cylindrical concrete columns and a central core structure, also made of concrete. The columns vary in diameter from 8 feet (2400 mm) at the base of the building to 4 feet (1200 mm) at the top. For speed of construction, the floors are framed with steel and composite metal decking. Concrete with strengths as high as 11,600 psi (80 MPa) was used in the columns. The architect was Cesar Pelli & Associates, Inc. The structural engineers were Thornton-Tomasetti and Rahnill Bersekutu Sdn Bhd. The U.S. partner in the joint venture team that constructed the towers was J. A. Jones Construction Co., Charlotte, North Carolina. *(Photograph by Uwe Hausen, J. A. Jones, Inc.)*

Figure 14.60
The Chapel of St. Ignatius, Seattle University, designed by architect Steven Holl, is a tilt-up concrete structure. *(Photo by Joseph Iano)*

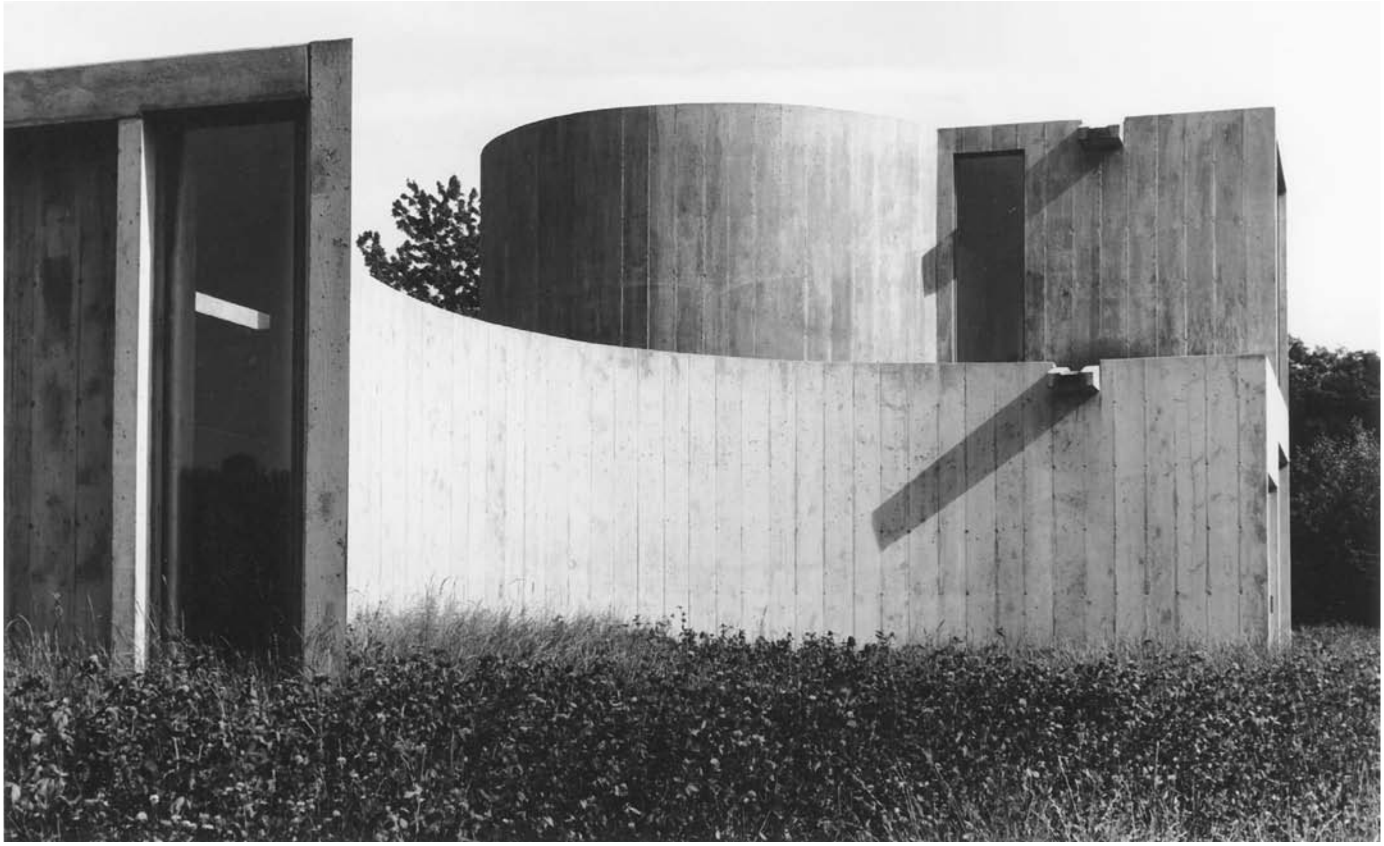


Figure 14.61
A sitecast concrete house in Lincoln, Massachusetts. *(Architects: Mary Otis Stevens and Thomas F. McNulty)*

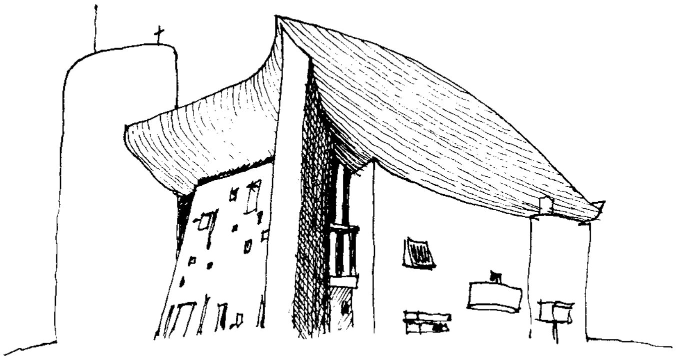


Figure 14.62
Le Corbusier's most sculptural building in his favorite material, concrete: the chapel of Notre Dame de Haut at Ronchamp, France (1950–1955). *(Drawing by Edward Allen)*

Figure 14.63
The TWA Terminal at John F. Kennedy Airport, New York, 1956–1962. *(Architect: Eero Saarinen. Photo by Wayne Andrews)*

CSI/CSC

MasterFormat Sections for Concrete Construction

03 30 00	CAST-IN-PLACE CONCRETE
03 31 00	Structural Concrete
03 33 00	Architectural Concrete
03 34 00	Low Density Concrete
03 35 00	Concrete Finishing
03 37 00	Specialty Placed Concrete
	Shotcrete
	Pumped Concrete
03 39 00	Concrete Curing

SELECTED REFERENCES

1. American Concrete Institute. *ACI 318: Building Code Requirements for Structural Concrete and Commentary*. Farmington Hills, MI, updated regularly.

This booklet establishes the basis for the engineering design and construction of reinforced concrete structures in the United States.

2. Concrete Reinforcing Steel Institute. *CRSI Design Handbook*. Schaumburg, IL, Concrete Reinforcing Steel Institute, updated regularly.

Structural engineers working in concrete use this handbook, which is based on the ACI Code (reference 1) as their major reference. It contains examples of engineering calculation methods and hundreds of pages of tables of standard designs for reinforced concrete structural elements.

3. Concrete Reinforcing Steel Institute. *Placing Reinforcing Bars*. Schaumburg, IL, updated regularly.

Written as a handbook for those engaged in the business of fabricating and placing reinforcing steel, this small volume is clearly written and beautifully illustrated with diagrams and photographs of reinforcing for all the common concrete framing systems.

4. Hurd, M. K. *Formwork for Concrete* (7th ed.). Farmington Hills, MI, American Concrete Institute, 2005.

Profusely illustrated, this book is the bible on formwork design and construction for sitecast concrete.

5. American Concrete Institute. *ACI 303R: Guide to Cast-in-Place Architectural Concrete Practice*. Farmington Hills, MI, updated regularly.

This is a comprehensive handbook on how to produce attractive surfaces in concrete.

6. Post-Tensioning Institute. *Post-Tensioning Manual*. Phoenix, AZ, updated regularly.

This heavily illustrated volume is both an excellent introduction to posttensioning for the beginner and a basic engineering manual for the expert.

8. Concrete Reinforcing Steel Institute. *Structural System Selection: Guide to Structural System Selection* and *Workbook for Evaluating Concrete Structures*. Schaumburg, IL, 1997.

These companion volumes make it easy to select an appropriate concrete framing system for a building and assign approximate sizes to its members.

9. See also the Selected References listed in Chapter 13.

WEB SITES

Sitecast Concrete Framing Systems

Author s supplementary web site: **www.ianosbackfill.com/14_sitecast_concrete_framing_systems**

Dayton Superior formwork accessories: **www.daytonconcreteacc.com**

Dywidag-Systems International posttensioning systems: **www.dsiamerica.com**

Molded Fiber Glass Construction Products Co. formwork: **www.mfgcp.com**

Symons Corp. formwork: **www.symons.com**

KEY TERMS AND CONCEPTS

slab on grade
capillary break
moisture barrier, vapor retarder
strike off, screed
floating
bull float
darby
bleed water
troweled slab
steel trowel
rotary power trowel
knee board
broom finish
restraightening
straightedge
shake-on hardener
curing compound
superflat concrete floor
F-number
control joint, contraction joint
isolation joint, expansion joint
shrinkage-compensating cement
key
dowel
form tie
waler
brace
formwork stripping
form tie hole
insulating concrete form (ICF)
one-way solid slab
shore
reshoring
slab band
one-way concrete joist system, ribbed slab
pan
distribution rib
joist band
wide-module concrete joist system, skip-joist system
two-way solid slab
two-way flat slab
mushroom capital
drop panel
column strip
middle strip
two-way flat plate
waffle slab, two-way concrete joist system
dome
head
draped tendon
set
lift-slab construction
ganged form
flying formwork
slip forming
tilt-up construction
shotcrete, pneumatically placed concrete
architectural concrete
exposed aggregate finish
rustication strip
diamond saw
barrel shell
folded plate

REVIEW QUESTIONS

1. Draw from memory a detail of a typical slab on grade and list the steps in its production. Why can't the surface be finished in one operation, instead of waiting for hours before final finishing?

2. What are control joints and isolation joints? Explain the purpose and typical locations for each in a concrete slab.

3. List the steps that are followed in forming and pouring a concrete wall.

4. Distinguish one-way concrete framing systems from two-way systems. Are steel and wood framing systems one-way or two-way? Is one-way construction more efficient structurally than two-way construction?

5. List the common one-way and two-way concrete framing systems and indicate the possibilities and limitations of each.

6. Why posttension a concrete structure rather than merely reinforce it?

EXERCISES

1. Propose a suitable reinforced concrete framing system for each of the following buildings and determine an approximate thickness for each:

   a. An apartment building with a column spacing of about 16 feet (5 m) in each direction

   b. A newsprint warehouse, column spacing 20 feet by 22 feet (6 m x 6.6 m)

   c. An elementary school, column spacing 24 feet by 32 feet (7.3 m x 9.75 m)

   d. A museum, column spacing 36 feet by 36 feet (11 m x 11 m)

   e. A hotel where overall building height must be minimized in order to build as many stories as possible within a municipal height limit

2. Look at several sitecast concrete buildings. Determine the type of framing system used in each and explain why you think it was selected. If possible, talk to the designers of the building and find out if you were right.

3. Observe a concrete building under construction. What is its framing system? Why? What types of forms are used for its columns, beams, and slabs? In what form are the reinforcing bars delivered to the site? How is the concrete mixed? How is it raised and deposited into the forms? How is it consolidated in the forms? How is it cured? Are samples taken for testing? How soon after pouring are the forms stripped? Are the forms reused? How long are the shores kept in place? Keep a diary of your observations over a period of a month or more.