2. *History of Concrete Building Construction*

2.1 Early Concrete

Much has been written about the numerous significant buildings of the Roman Empire constructed using "concrete" as the primary structural material. Many researchers believe that the first use of a truly cementitious binding agent (as opposed to the ordinary lime commonly used in ancient mortars) occurred in southern Italy in about the second century B.C. A Special type of volcanic sand called *pozzuolana*, first found near Pozzuoli in the bay of Naples, was used extensively by the Romans in their cement. It is certain that to build the Porticus Aemelia, a large warehouse constructed in 193 B.C., pozzuolana was used to bind stones together to make "concrete." This unusual sand reacts chemically with lime and water to solidify into a rocklike mass, even when fully submerged. The Romans used it for bridges, docks, storm drains, and aqueducts as well as for buildings.

Roman concrete bears little resemblance to modern Portland cement concrete. It was never in a plastic state that could flow into a mold or a construction of formwork. Indeed, there is no clear dividing line between what could be called the first concrete and what might be more correctly termed cemented rubble. Roman concrete was constructed in layers by packing mortar by hand in and around stones of various sizes. This assembly was faced with clay bricks on both sides, unless it was below grade, and in the case of walls the wythes of bricks served as forms for the "concrete" (Boethius and Ward-Perkins, 1970). It is known that the bricks had little structural value and were used to facilitate construction and as surface decoration. There is little doubt that the pozzuolanic material made this type of construction possible, as it was used throughout the Rome/Naples area but is not seen in northern Italy nor elsewhere in the Roman Empire.

Most public buildings, including the Pantheon, and fashionable residences in Rome used brick faced concrete construction for walls and vaults. The domed Pantheon, constructed in the second century A.D., is certainly one of the structural masterpieces of all time. It is a highly sophisticated structure with many weight-reducing voids, niches, and small vaulted spaces. The builders of the Pantheon knew enough to use very heavy aggregates at the ground level and ones of decreasing density higher up in the walls and in the dome itself in order to reduce the weight to be carried. The Pantheon's clear span of 142 ft dwarfed previous spans and created nothing less than an architectural revolution in terms of the way interior space was perceived (Mainstone, 1975)

Probably due to the lack of availability of similar pozzuolans throughout the world, this type of concrete was not used elsewhere and stone and brick masonry continued to be the dominant construction materials for most of the world's significant buildings for many centuries. A type of concrete was first seen again in eighteenth-century France, where stuccoed rubble made to emulate true masonry became fashionable. Francois Cointeraux, a mason in Lyon, searched for an economical means of making fireproof walls by using cementitious mortar in combination with the very ancient pise or "rammed earth" construction technique (Collins, 1959). Pise calls for the use of timber formwork to contain the clay or mud while it is being compacted, but the use of new and stronger cements made the compacting process unnecessary. In 1824 Joseph Aspdin, an English mason, patented an improved cement which he called Portland cement because it resembled a natural stone quarried on the nearby Isle of Portland. It is generally believed that Aspdin was the first to use high temperatures to heat alumina and silica materials to the point of vitrification, which resulted in fusion. Cement is still made this way today. During the nineteenth century concrete was used for many buildings in Europe, often of an industrial nature, as this "new" material did not have the social acceptability of stone or brick.

2.2 The Use of Reinforcing

Disagreement exists among researchers as to the first real use of reinforcing in concrete. More often than not, the construction of several small rowboats by Jean-Louis Lambot in the early 1850s is cited as the first successful example. Mr. Lambot, a gentleman farmer in southern France, reinforced his boats with iron bars and wire mesh. He had some plans for using this material in building construction because he applied for a patent in France and Belgium in 1856, describing concrete as follows (Cassie, 1965):

> *An Improved Building Material to be used as a Substitute for Wood in Naval and Architectural Constructions and also for Domestic Purposes where Dampness is to be Avoided.*

In 1854 a plasterer, William B. Wilkinson of Newcastle-upon-Tyne, erected a small two-story servant's cottage, reinforcing the concrete floor and roof with iron bars and wire rope, and took out a patent on this type of construction in England (Condit, 1968). He built several such structures and is properly credited with constructing the first reinforced concrete building.

In 1867 Joseph Monier, a French gardener, took out a patent on some reinforced garden tubs and later patented some reinforced beams and posts used for guardrails for roads and railways. It was subsequently shown that Monier never understood, as Wilkinson had, the need for the reinforcing to be near the tensile side of a beam.

The first widespread use of Portland cement concrete in buildings occurred under the direction of the French builder, Francois Coignet. He built several large houses of concrete in England and France in the period 1850-1880, at first using iron rods in the floors to keep the walls from spreading, but later using the rods as flexural elements (Farebrother, 1962)

The first landmark building in reinforced concrete was built by an American mechanical engineer, William E. Ward, in 1871-1875. The house stands today in Port Chester, NY. It is well-known because of the diligence with which Mr. Ward conducted all of his business, researching and documenting everything. He desired a concrete house because his wife was terribly afraid of fire and commissioned architect Robert Mook for the design in 1870. Like Coignet's buildings, it was made to resemble masonry to be socially acceptable. Mr. Ward handled all technical and construction issues himself, conducting long-term load tests and other experiments. He used the French word for concrete, *beton*, and in 1883 delivered a paper on the house to the American Society of Mechanical Engineers entitled "Beton in Combination with Iron As a Building Material." His audience, by definition, was far more interested in the unique water supply and heating systems, which he had designed, than in reinforced concrete.

In 1879 G. A. Wayss, a German builder, bought the patent rights to Monier's system and pioneered reinforced concrete construction in Germany and Austria, promoting the Wayss-Monier system (Collins, 1959). (Many of these buildings were built in France as well).

2.3 Monolithic Frame Construction

The late nineteenth century saw the parallel development of reinforced concrete frame construction by G. A. Wayss in Germany/ Austria, by Ernest L. Ransome in the United States, and by Francois Hennebique in France.

In the 1870s Ernest L. Ransome was managing a successful stone company (producing concrete blocks as artificial stone) in San Francisco. He first used reinforcing in 1877, and in 1884 he patented a system using twisted square rods to help the development of bond between the concrete and reinforcing (Collins, 1959). His largest work of the time was the Leland Stanford, Jr. Museum at Stanford University, the first building to use exposed aggregate. He was also responsible for several industrial buildings in New Jersey and Pennsylvania, such as the 1903-1904 construction of the Kelly and Jones Machine Shop in Greensburg, Pennsylvania.

The Ingalls Building, a landmark structure in Cincinnati, was built in 1904 using a variation of the Ransome system. Designed by the firm of Elzner and Henderson, it was the first concrete skyscraper, reaching 16 stories (210 feet).

On the other side of the Atlantic, Francois Hennebique, a successful mason turned contractor in Paris, had started to build reinforced concrete houses in the late 1870s. He took out patents in France and Belgium for the Hennebique system of construction and proceeded to establish an empire of franchises in major cities. He promoted the material by holding conferences and developing standards within his own company network. Most of his buildings (like Ransome's) were industrial.

When the far-flung company was at its' peak, Hennebique was fulfilling more than 1500 contracts annually (Collins, 1959). More than any other individual he was responsible for the rapid growth of reinforced concrete construction in Europe.

2.4 A Reinforced Concrete Architecture

If Hennebique was responsible for the acceptability of reinforced concrete as a building material, then it was Auguste Ferret who made it acceptable as an architectural material. The works of Ferret include not only factories and apartment buildings, but also museums, churches, and theaters. His better known works are in or around Paris, such as the delicately facaded apartment building at 25 bis Rue Franklin, completed in 1903. Just a few years later he designed the bulky, massive-looking, but spacious Theatre Champs Elysee.

Notre Dame du Raincy, constructed in 1922, represented a significant departure from anything built in concrete before and is generally regarded as a masterpiece of architectural design. The lofty arched ceilings and the slender columns were very convincing statements as to the prowess of this newly accepted building material.

2.5 Shell Construction

Reinforced concrete permitted the development of an entirety new building form-the thin shell. In 1930 Eduardo Torroja, the brilliant Spanish engineer, designed a low-rise dome of 3.5-in thickness and 150-ft span for the market at Algeciras, using steel cables for a tension ring. Torroja was also responsible for the statically elegant cantilevered stadium roof at the Madrid Hippodrome in 1935.

At about the same time the Italian architect-engineer, Pier Luigi Nervi, began building his famous hangars for the Italian Air Force. At first these were cast in situ, but most of Nervi's work, including the Exhibition Hall at Turin and the two sports palaces in Rome, was primarily of precast construction.

The master of the concrete shell, without dispute, would be the Spanish-born mathematician-engineer-architect, Felix Candela. Practicing mostly in Mexico City, he designed the Cosmic Ray Laboratory, with a 5/8 inch thick shell roof, for the University of Mexico City. He adopted the hyperbolic paraboloid form as his trademark and, making use of favorable labor costs, built many factories and churches in and around Mexico City using this form. His most striking building is the restaurant at Xochimilco, built in 1958, consisting of six identical paraboloid vaults.

2.6 Further Uses of Concrete in Modern Architecture

As a young architect Le Corbusier worked part-time in Perret's office but was always at odds with his employer, having no use for the espoused classical basis for design (Collins, 1959). Le Corbusier was later to become the most highly regarded architect of the modern era, building almost exclusively in reinforced concrete. Among his celebrated works are the Villa Savoye (of flat plate construction, 1931), the housing blocks on pilotis at Nantes and Marseille (late 1940s), the Chapel at Ronchamp (with walls of concreted masonry construction, 1957), the monastery of La Tourette (1959), and the government complex at Chandigarh in India (1961). More so than his contemporaries, Le Corbusier was involved with the play of natural light as a design element, and concrete with its variable surface texture provided an excellent medium for his efforts.

Frank Lloyd Wright declared the prime assets of reinforced concrete to be its formability and monolithic property of construction, but he did not take advantage of this until late in his career. He was the first to exploit the cantilever as a design feature made possible by the continuous nature of reinforced concrete construction. The Kaufman House (Fallingwater), built in 1936, is a tour de force in the use of the cantilever. Thin slabs seem to project beyond the possible, perhaps constructed containing as much steel as concrete!

In 1919 Mies van der Rohe had proposed the idea of a structural core for a high-rise building with cantilevered floor slabs (Drexler, 1960), but it was not until 1947 that Wright brought the idea to fruition with his design for the Johnson Wax Tower at Racine, Wisconsin. The entire Johnson Wax headquarters complex was hailed as being among the best of Wright's creations.

Wright's claim to an organic basis for his designs and the need to exploit the "plastic" nature of reinforced concrete reached a high point with his design of the Guggenheim Museum in 1956. The monumental spiral form became an overnight New York City landmark.

2.7 High-strength Concrete and High-Rise Buildings

High-rise construction in concrete progressed slowly forward from the Ingalls Building in 1904. The giants and midgiants of the 1930s were all of steel construction. The Johnson Wax Tower, however, provided the impetus for Bertrand Goldberg's twin towers of Marina City, though on a vastly different scale. The Chicago 60story high-rise, erected in 1962, heralded the beginning of the use of reinforced concrete in modern skyscrapers and with it, competition for the steel frame. Place Victoria in Montreal, constructed in 1964, reached height of 624 ft utilizing 6000 psi concrete in the columns. Concretes of higher strength proved to be the key to increased height, permitting as they do a reasonable column size on the floors below. One Shell Plaza in Houston topped out at 714 ft in 1970 using 6000 psi concrete. The Chicage area, with its plentiful supply of high quality fly ash (which helps to achieve a more workable concrete at lower water/cement ratios), has spawned the greatest concentration of tall reinforced concrete buildings. The 70-story Lake Point Towers used 7500 psi concrete to reach 645 ft in 1968. Water Tower Place reached 859 feet in 1973 with concrete strengths as high as 9000 psi thanks to a superplasticizing admixture (see Section 3.5).

In 1989 the Scotia Plaza Building in Toronto was completed to a height of 907 ft. In 1990 two more towers in Chicago exceeded 900 ft. The taller of these is the building at 311 S. Wacker Drive shown next to the Sears Tower. Even taller buildings are now planned for New York, Chicago, and Tokyo using concretes of 15,000 psi and higher.

3. *History of Concrete Building Construction*

3.1 Properties of Concrete

Concrete is an artificial conglomerate stone made essentially of Portland cement, water, and aggregates. When first mixed the water and cement constitute a paste which surrounds all the individual pieces of aggregate to make a plastic mixture. A chemical reaction called hydration takes place between the water and cement, and concrete normally changes from a plastic to a solid state in about 2 hours. Thereafter the concrete continues to gain strength as it cures. A typical strength-gain curve is shown in Figure 13. The industry has adopted the 28-day strength as a reference point, and specifications often refer to compression tests of cylinders of concrete which are crushed 28 days after they are made. The resulting strength is given the designation f'_c

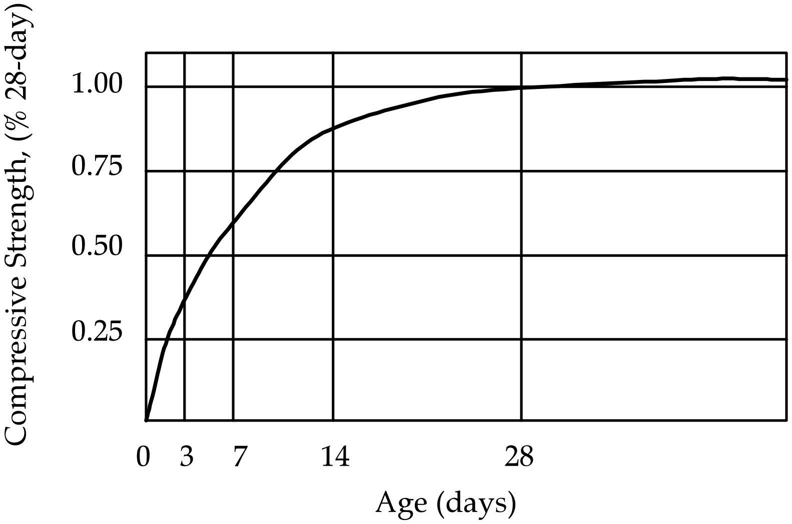

Figure 13. Typical strength-gain curve.

During the first week to 10 days of curing it is important that the concrete not be permitted to freeze or dry out because either of these, occurrences would be very detrimental to the strength development of the concrete. Theoretically, if kept in a moist environment, concrete will gain strength forever, however, in practical terms, about 90% of its strength is gained in the first 28 days.

Concrete has almost no tensile strength (usually measured to be about 10 to 15% of its compressive strength), and for this reason it is almost never used without some form of reinforcing. Its compressive strength depends upon many factors, including the quality and proportions of the ingredients and the curing environment. The single most important indicator of strength is the ratio of the water used compared to the amount of cement. Basically, the lower this ratio is, the higher the final concrete strength will be. (This concept was developed by Duff Abrams of The Portland Cement Association in the early 1920s and is in worldwide use today.) A minimum *w/c ratio* (water-to-cement ratio) of about 0.3 by weight is necessary to ensure that the water comes into contact with all cement particles (thus assuring complete hydration). In practical terms, typical values are in the 0.4 to 0.6 range in order to achieve a workable consistency so that fresh concrete can be placed in the forms and around closely spaced reinforcing bars.

Typical stress-strain curves for various concrete strengths are shown in Figure 14. Most structural concretes have f'_c values in the 3000 to 5000 psi range. However, lowerstory columns of high-rise buildings will sometimes utilize concretes of 12,000 or 15,000 psi to reduce the column dimensions which would otherwise be inordinately large. Even though Figure 14 indicates that the maximum strain that concrete can sustain before it crushes varies inversely with strength, a value of 0.003 is usually taken (as a simplifying measure) for use in the development of design equations.

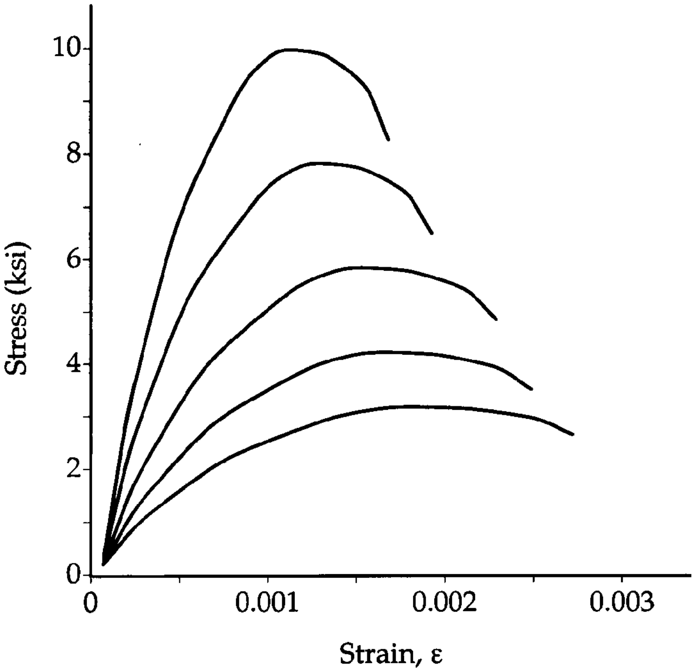

Figure 14.. Stress versus Strain curves.

Because concrete has no linear portion to its stress-strain curve, it is difficult to measure a proper modulus of elasticity value. For concretes up to about 6000 psi it can be approximated as

$$\boxed{E = 33w^{1.5}\sqrt{f'_c}} \qquad (3\text{–}1)$$

where w is the unit weight (pcf), f'_c is the cylinder strength (psi). (It is important that the units of f'_c be expressed in psi and not ksi whenever the square root is taken). The weight density of reinforced concrete using normal sand and stone aggregates is about 150 pcf. If 5 pcf of this is allowed for the steel and w is taken as 145 in Equation (2-1), then

$$\boxed{E = 57,000\sqrt{f'_c}} \tag{3–6}$$

E values thus computed have proven to be acceptable for use in deflection calculations.

As concrete cures it shrinks because the water not used for hydration gradually evaporates from the hardened mix. For large continuous elements such shrinkage can result in the development of excess tensile stress, particularly if a high water content brings about a large shrinkage. Concrete, like all materials, also undergoes volume changes due to thermal effects, and in hot weather the heat from the exothermic hydration process adds to this problem. Since concrete is weak in tension, it will often develop cracks due to such shrinkage and temperature changes. For example, when a freshly placed concrete slab-on-grade expands due to temperature change, it develops internal compressive stresses as it overcomes the friction between it and the ground surface. Later when the concrete cools land shrinks as it hardens) and tries to contract, it is not strong enough in tension to resist the same frictional forces. For this reason contraction joints are often used to control the location of cracks that inevitably occur and so-called temperature and shrinkage reinforcement is placed in directions where reinforcing has not already been specified for other reasons. The purpose of this reinforcing is to accommodate the resulting tensile stresses and to minimize the width of cracks that do develop.

In addition to strains caused by shrinkage and thermal effects, concrete also deforms due to creep. Creep is Increasing deformation that takes place when a material sustains a high stress level over a long time period. Whenever constantly applied loads (such as dead loads) cause significant compressive stresses to occur, creep will result. In a beam, for example, the additional longterm deflection due to creep can be as much as two times the initial elastic deflection The way to avoid this increased deformation is to keep the stresses due to sustained loads at a low level. This is usually done by adding compression steel.

3.2 Mix Proportions

The ingredients of concrete can be proportioned by weight or volume. The goal is to provide the desired strength and workability at minimum expense. Sometimes there are special requirements such as abrasion resistance, durability in harsh climates, or water impermeability, but these properties are usually related to strength. Sometimes concretes of higher strength are specified even though a lower f'_c value would have met all structural requirements.

As mentioned previously, a low water-to-cement ratio is needed to achieve strong concrete. It would seem therefore that by merely keeping the cement content high one could use enough water for good workability and still have a low w/c ratio. The problem is that cement is the most costly of the basic ingredients. The dilemma is easily seen in the schematic graphs of Figure 15.

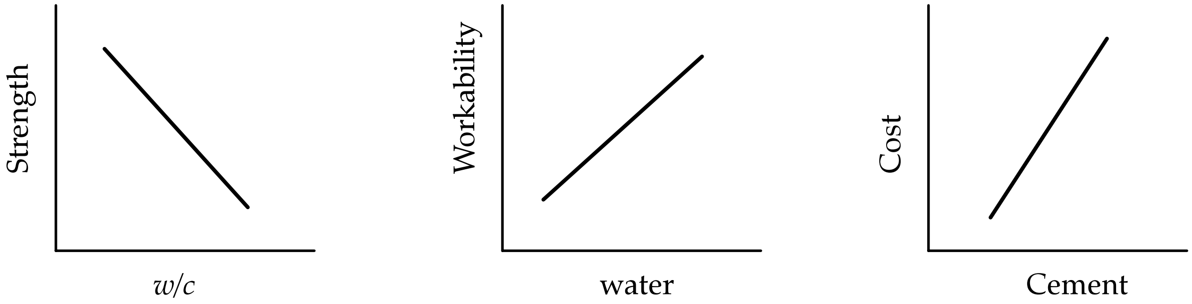

Figure 15. Mix Proportion relationships.

Since larger aggregate sizes have relatively smaller surface areas (for the cement paste to coat) and since less water means less cement, it is often said that one should use the largest practical aggregate size and the stiffest practical mix. (Most building elements are constructed with a maximum aggregate size of 3/4 to 1 in, larger sizes being prohibited by the closeness of the reinforcing bars.)

A good indication of the water content of a mix land thus the workability) can be had from a standard slump test. In this test a metal cone 12 in tall is filled with fresh concrete in a specified manner. When the cone is lifted, the mass of concrete "slumps" downward (Figure 16) and the vertical drop is referred to as the slump. Most concrete mixes have slumps in the 2- to 5-in range.

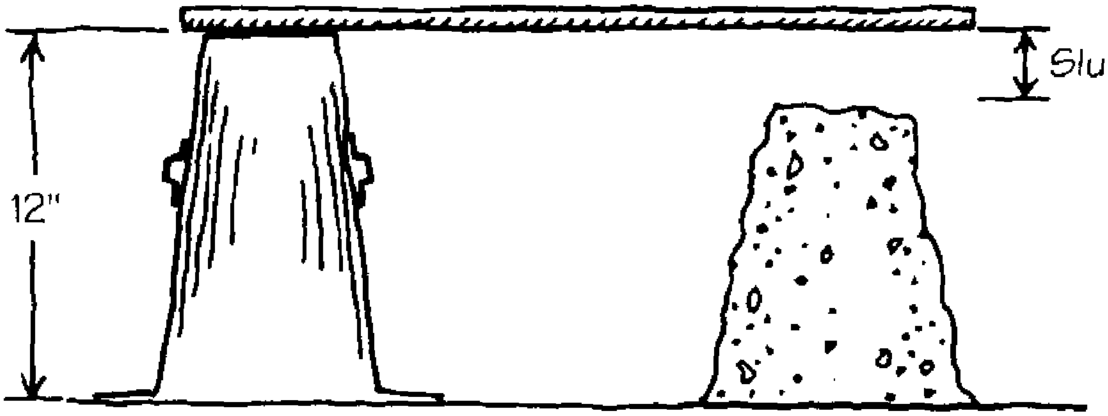

Figure 16. Slump Test..

3.3 Portland Cement

The raw ingredients of Portland cement are iron ore, lime, alumina and silica, which are used in various proportions depending upon the type of cement being made. These are ground up and fired in a kiln to produce a clinker. After cooling, the clinker is very finery ground (to about the texture of talcum powder) and a small amount of gypsum is added to retard the initial setting time. There are five basic types of Portland cement in use today:

Type I	General purpose
Type II	Sulfate resisting, concrete in contact with high sulfate soils
Type III	High early strength, which gains strength faster than Type I, Enabling forms to be removed sooner
Type IV	Low heat of hydration, for use in massive construction
Type V	Severe sulfate resisting

Type I is the least expensive and is used for the majority of concrete structures. Type III is also frequently employed because it enables forms to be reused quickly, allowing construction time to be reduced. It is important to note that while Type II gains strength faster than Type I, it does not take its initial set any sooner).

3.4 Aggregates

Fine aggregate (sand) is made up of particles which can pass through a 3/8 in sieve; coarse aggregates are larger than 3/8 inch in size. Aggregates should be clean, hard, and well-graded, without natural cleavage planes such as those that occur in slate or shale. The quality of aggregates is very important since they make up about 60 to 75% of the volume of the concrete; it is impossible to make good concrete with poor aggregates. The grading of both fine and coarse aggregate is very significant because having a full range of sizes reduces the amount of cement paste needed. Well-graded aggregates tend to make the mix more workable as well.

Normal concrete is made using sand and stones, but lightweight concrete can be made using industrial by-products such as expanded slag or clay as lightweight aggregates. This concrete weighs only 90 to 125 pcf and high strengths are more difficult to achieve because of the weaker aggregates. However, considerable savings can be realized in terms of the building self-weight, which may be very important when building on certain types of soil. Insulating concrete is made using perlite and vermiculite, it weighs only about 15 to 40 pcf and has no structural value.

3.5 Admixtures

Admixtures are chemicals which are added to the mix to achieve special purposes or to meet certain construction conditions. There are basically four types: air-entraining agents, workability agents, retarding agents, and accelerating agents.

In climates where the concrete will be exposed to freeze-thaw cycles air is deliberately mixed in with the concrete in the form of billions of tiny air bubbles about 0.004 in in diameter. The bubbles provide interconnected pathways so that water near the surface can escape as it expands due to freezing temperatures. Without air-entraining, the surface of concrete will almost always spall off when subjected to repeated freezing and thawing. (Air-entraining also has the very beneficial side effect of increasing workability without an increase in the water content.) Entrained air is not to be confused with entrapped air, which creates much larger voids and is caused by improper placement and consolidation of the concrete. Entrapped air, unlike entrained air, is never beneficial.

Workability agents, which include waterreducing agents and plasticizers, serve to reduce the tendency of cement particles to bind together in flocs and thus escape complete hydration. Fly ash, a by-product of the burning of coal that has some cementitious properties, is often used to accomplish a similar purpose. Superplasticizers are relatively new admixtures which when added to a mixture serve to increase the slump greatly, making the mixture very soupy for a short time and enabling a low-water-content tor otherwise very stiff) concrete to be easily placed. Superplasticizers are responsible for the recent development of very high strength concretes, some in excess of 15,000 psi because they greatly reduce the need for excess water for workability.

Retarders are used to slow the set of concrete when large masses must be placed and the concrete must remain plastic for a long period of time to prevent the formation of “cold joints” between one batch of concrete and the next batch. Accelerators serve to increase the rate of strength gain and to decrease the initial setting time. This can be beneficial when concrete must be placed on a steep slope with a single form or when it is desirable to reduce the time period in which concrete must be protected from freezing. The best known accelerator is calcium chloride, which acts to increase the heat of hydration, thereby causing the concrete to set up faster.

Other types of chemical additives are available for a wide range of purposes. Some of these can have deleterious side effects on strength gain, shrinkage, and other characteristics of concrete, and test batches are advisable if there is any doubt concerning the use of a particular admixture.

3.6 The ACI Code

The American Concrete Institute (ACI), based in Detroit, Michigan, is an organization of design professionals, researchers, producers, and constructors. One of its functions is to promote the safe and efficient design and construction of concrete structures. The ACI has numerous publications to assist designers and builders; the most important one in terms of building structures is entitled *Building Code Requirements for Reinforced Concrete and Commentary*. It is produced by Committee 318 of the American Concrete Institute and contains the basic guidelines for building code officials, architects, engineers, and builders regarding the use of reinforced concrete for building structures. Information is presented concerning materials and construction practices, standard tests, analysis and design, and structural systems. This document has been adopted by most building code authorities in the United States as a standard reference. It provides all rules regarding reinforcing sizes, fabrication, and placement and is an invaluable resource for both the designer and the detailer.

Periodic updates occur (1956, 1963, 1971, 1977, 1983, and 1989), and this text makes constant reference to the 1989 edition, calling it the ACI Code or merely the Code. Documents and officials also refer to it by its numerical designation, ACI 318-89.

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