

# CHAPTER 1 Fundamentals of Concrete

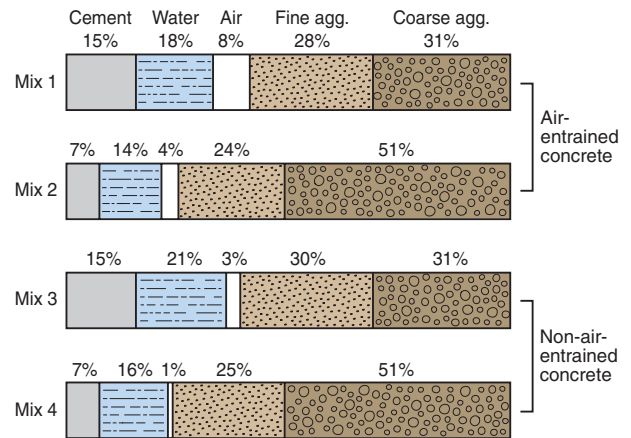
Concrete is basically a mixture of two components: aggregates and paste. The paste, comprised of portland cement and water, binds the aggregates (usually sand and gravel or crushed stone) into a rocklike mass as the paste hardens because of the chemical reaction of the cement and water (Fig. 1-1). Supplementary cementitious materials and chemical admixtures may also be included in the paste.\*

Aggregates are generally divided into two groups: fine and coarse. Fine aggregates consist of natural or manufactured sand with particle sizes ranging up to 9.5 mm (3/8 in.); coarse aggregates are particles retained on the 1.18 mm (No. 16) sieve and ranging up to 150 mm (6 in.) in size. The maximum size of coarse aggregate is typically 19 mm (3/4 in. or 1 in.). An intermediate-sized aggregate, around 9.5 mm (3/8 in.), is sometimes added to improve the overall aggregate gradation.



**Fig. 1-1. Concrete components: cement, water, fine aggregate and coarse aggregate, are combined to form concrete. (55361)**

\* This text addresses the utilization of portland cement in the production of concrete. The term "portland cement" pertains to a calcium silicate hydraulic cement produced by heating materials containing calcium, silicon, aluminum, and iron. The term "cement" used throughout the text pertains to portland cement or blended hydraulic cement unless otherwise stated. The term "cementitious materials" means portland or blended cement, used with or without supplementary cementitious materials.

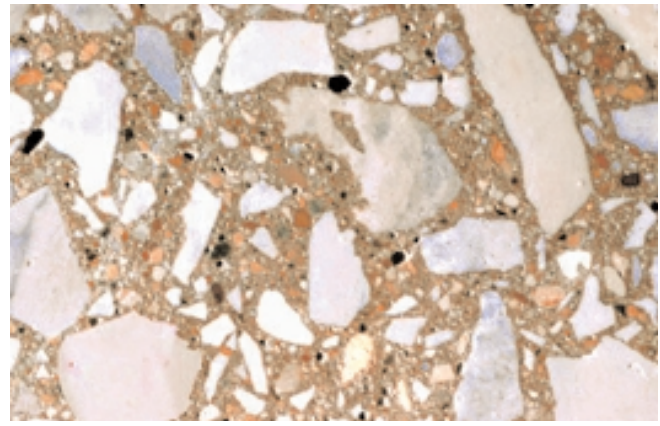
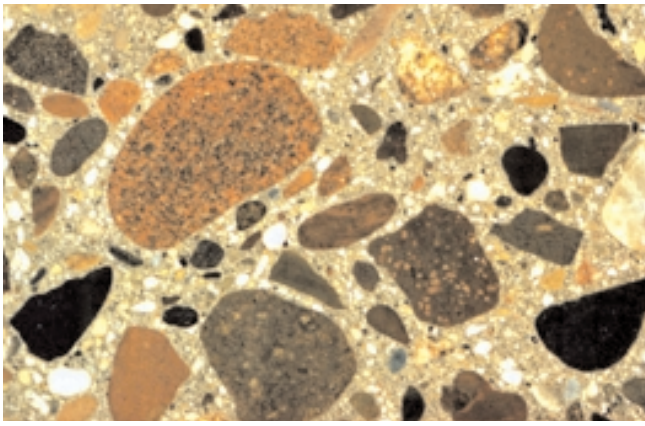


**Fig. 1-2. Range in proportions of materials used in concrete, by absolute volume. Bars 1 and 3 represent rich mixes with small size aggregates. Bars 2 and 4 represent lean mixes with large size aggregates.**

The paste is composed of cementitious materials, water, and entrapped air or purposely entrained air. The paste constitutes about 25% to 40% of the total volume of concrete. Fig. 1-2 shows that the absolute volume of cement is usually between 7% and 15% and the water between 14% and 21%. Air content in air-entrained concrete ranges from about 4% to 8% of the volume.

Since aggregates make up about 60% to 75% of the total volume of concrete, their selection is important. Aggregates should consist of particles with adequate strength and resistance to exposure conditions and should not contain materials that will cause deterioration of the concrete. A continuous gradation of aggregate particle sizes is desirable for efficient use of the paste. Throughout this text, it will be assumed that suitable aggregates are being used, except where otherwise noted.

The quality of the concrete depends upon the quality of the paste and aggregate, and the bond between the two. In properly made concrete, each and every particle of aggregate is completely coated with paste and all of the spaces between aggregate particles are completely filled with paste, as illustrated in Fig. 1-3.

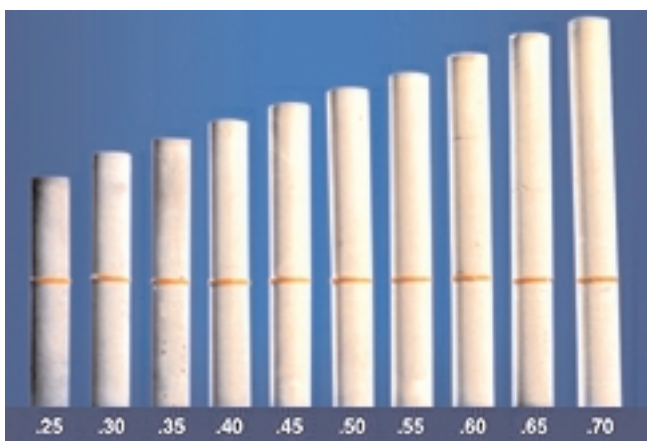


**Fig. 1-3. Cross section of hardened concrete made with (left) rounded siliceous gravel and (right) crushed limestone. Cement-and-water paste completely coats each aggregate particle and fills all spaces between particles. (1051, 1052)**

For any particular set of materials and conditions of curing, the quality of hardened concrete is strongly influenced by the amount of water used in relation to the amount of cement (Fig. 1-4). Unnecessarily high water contents dilute the cement paste (the glue of concrete). Following are some advantages of reducing water content:

- Increased compressive and flexural strength
- Lower permeability, thus lower absorption and increased watertightness
- Increased resistance to weathering
- Better bond between concrete and reinforcement
- Reduced drying shrinkage and cracking
- Less volume change from wetting and drying

The less water used, the better the quality of the concrete—provided the mixture can be consolidated properly. Smaller amounts of mixing water result in stiffer mixtures; but with vibration, stiffer mixtures can be easily placed. Thus, consolidation by vibration permits improvement in the quality of concrete.



**Fig. 1-4. Ten cement-paste cylinders with water-cement ratios from 0.25 to 0.70. The band indicates that each cylinder contains the same amount of cement. Increased water dilutes the effect of the cement paste, increasing volume, reducing density, and lowering strength. (1071)**

The freshly mixed (plastic) and hardened properties of concrete may be changed by adding chemical admixtures to the concrete, usually in liquid form, during batching. Chemical admixtures are commonly used to (1) adjust setting time or hardening, (2) reduce water demand, (3) increase workability, (4) intentionally entrain air, and (5) adjust other fresh or hardened concrete properties.

After completion of proper proportioning, batching, mixing, placing, consolidating, finishing, and curing, concrete hardens into a strong, noncombustible, durable, abrasion-resistant, and watertight building material that requires little or no maintenance. Furthermore, concrete is an excellent building material because it can be formed into a wide variety of shapes, colors, and textures for use in an unlimited number of applications.

## FRESHLY MIXED CONCRETE

Freshly mixed concrete should be plastic or semifluid and generally capable of being molded by hand. A very wet concrete mixture can be molded in the sense that it can be cast in a mold, but this is not within the definition of “plastic”—that which is pliable and capable of being molded or shaped like a lump of modeling clay.

In a plastic concrete mixture all grains of sand and pieces of gravel or stone are encased and held in suspension. The ingredients are not apt to segregate during transport; and when the concrete hardens, it becomes a homogeneous mixture of all the components. During placing, concrete of plastic consistency does not crumble but flows sluggishly without segregation.

In construction practice, thin concrete members and heavily reinforced concrete members require workable, but never soupy, mixes for ease of placement. A plastic mixture is required for strength and for maintaining homogeneity during handling and placement. While a plastic mixture is suitable for most concrete work, plasticizing admixtures may be used to make concrete more flowable in thin or heavily reinforced concrete members.

## Mixing

In Fig. 1-1, the basic components of concrete are shown separately. To ensure that they are combined into a homogeneous mixture requires effort and care. The sequence of charging ingredients into a concrete mixer can play an important part in uniformity of the finished product. The sequence, however, can be varied and still produce a quality concrete. Different sequences require adjustments in the time of water addition, the total number of revolutions of the mixer drum, and the speed of revolution. Other important factors in mixing are the size of the batch in relation to the size of the mixer drum, the elapsed time between batching and mixing, and the design, configuration, and condition of the mixer drum and blades. Approved mixers, correctly operated and maintained, ensure an end-to-end exchange of materials by a rolling, folding, and kneading action of the batch over itself as concrete is mixed.

## Workability

The ease of placing, consolidating, and finishing freshly mixed concrete and the degree to which it resists segregation is called workability. Concrete should be workable but the ingredients should not separate during transport and handling (Fig. 1-5).

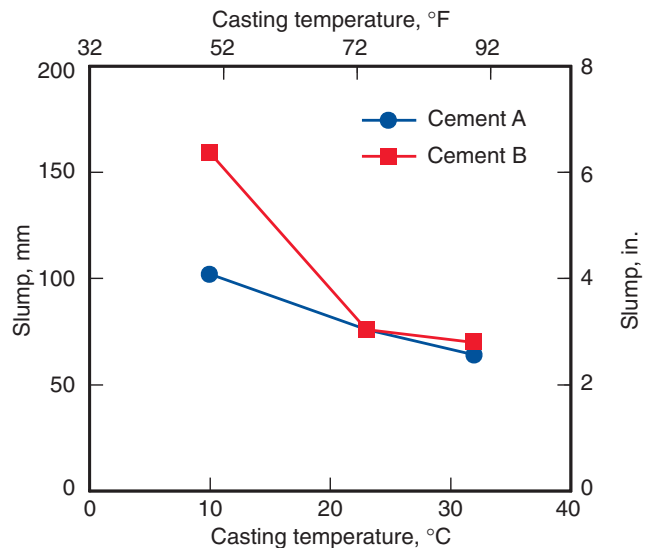
The degree of workability required for proper placement of concrete is controlled by the placement method, type of consolidation, and type of concrete. Different types of placements require different levels of workability.

Factors that influence the workability of concrete are: (1) the method and duration of transportation; (2) quantity and characteristics of cementitious materials; (3) concrete consistency (slump); (4) grading, shape, and surface texture of fine and coarse aggregates; (5) entrained air; (6) water content; (7) concrete and ambient air temperatures; and (8) admixtures. A uniform distribution of aggregate particles and the presence of entrained air significantly help control segregation and improve workability. Fig. 1-6 illustrates the effect of casting temperature on the consistency, or slump, and potential workability of concrete mixtures.

Properties related to workability include consistency, segregation, mobility, pumpability, bleeding, and finishability. Consistency is considered a close indication of workability. Slump is used as a measure of the consistency or wetness of concrete. A low-slump concrete has a stiff consistency. If



**Fig. 1-5. Workable concrete should flow sluggishly into place without segregation. (59292)**

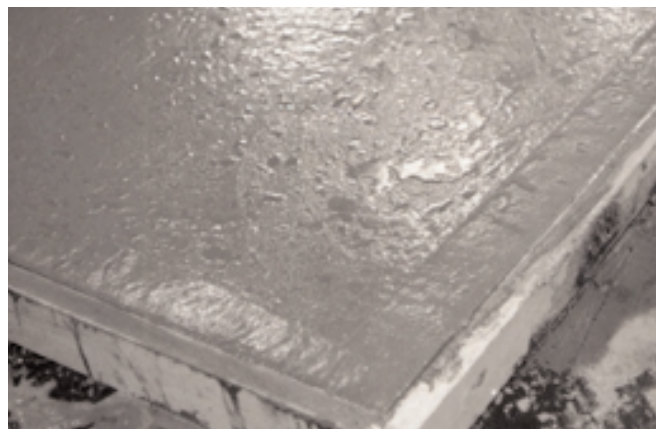


**Fig. 1-6. Effect of casting temperature on the slump (and relative workability) of two concretes made with different cements (Burg 1996).**

the consistency is too dry and harsh, the concrete will be difficult to place and compact and larger aggregate particles may separate from the mix. However, it should not be assumed that a wetter, more fluid mix is necessarily more workable. If the mix is too wet, segregation and honeycombing can occur. The consistency should be the driest practicable for placement using the available consolidation equipment. See Powers (1932) and Scanlon (1994).

## Bleeding and Settlement

Bleeding is the development of a layer of water at the top or surface of freshly placed concrete. It is caused by sedimentation (settlement) of solid particles (cement and aggregate) and the simultaneous upward migration of water (Fig. 1-7). Bleeding is normal and it should not diminish the quality of properly placed, finished, and cured concrete. Some bleeding is helpful to control plastic shrinkage cracking.



**Fig. 1-7. Bleed water on the surface of a freshly placed concrete slab. (P29992)**



Excessive bleeding increases the water-cement ratio near the top surface; a weak top layer with poor durability may result, particularly if finishing operations take place while bleed water is present. A water pocket or void can develop under a prematurely finished surface.

After evaporation of all bleed water, the hardened surface will be slightly lower than the freshly placed surface. This decrease in height from time of placement to initial set is called settlement shrinkage.

The bleeding rate and bleeding capacity (total settlement per unit of original concrete height) increases with initial water content, concrete height, and pressure. Use of properly graded aggregate, certain chemical admixtures, air entrainment, supplementary cementitious materials, and finer cements, reduces bleeding. Concrete used to fill voids, provide support, or provide watertightness with a good bond should have low bleeding properties to avoid formation of water pockets. See Powers (1939), Steinoor (1945), and Kosmatka (1994).



Fig. 1-8. Good consolidation (left) is needed to achieve a dense and durable concrete. Poor consolidation (right) can result in early corrosion of reinforcing steel and low compressive strength. (70016, 68806)

## Consolidation

Vibration sets into motion the particles in freshly mixed concrete, reducing friction between them, and giving the mixture the mobile qualities of a thick fluid. The vibratory action permits use of a stiffer mixture containing a larger proportion of coarse and a smaller proportion of fine aggregate. The larger the maximum size aggregate in concrete with a well-graded aggregate, the less volume there is to fill

with paste and the less aggregate surface area there is to coat with paste; thus less water and cement are needed. Concrete with an optimally graded aggregate will be easier to consolidate and place (Fig. 1-8 left). Consolidation of coarser as well as stiffer mixtures results in improved quality and economy. On the other hand, poor consolidation can result in porous, weak concrete (Fig. 1-9) with poor durability (Fig. 1-8 right).

Mechanical vibration has many advantages. Vibrators make it possible to economically place mixtures that are impractical to consolidate by hand under many conditions. As an example, Fig. 1-10 shows concrete of a stiff consistency (low slump). This concrete was mechanically vibrated in forms containing closely spaced reinforcement. With hand rodding, a much wetter consistency would have been necessary.



Fig. 1-10. Concrete of a stiff consistency (low slump). (44485)

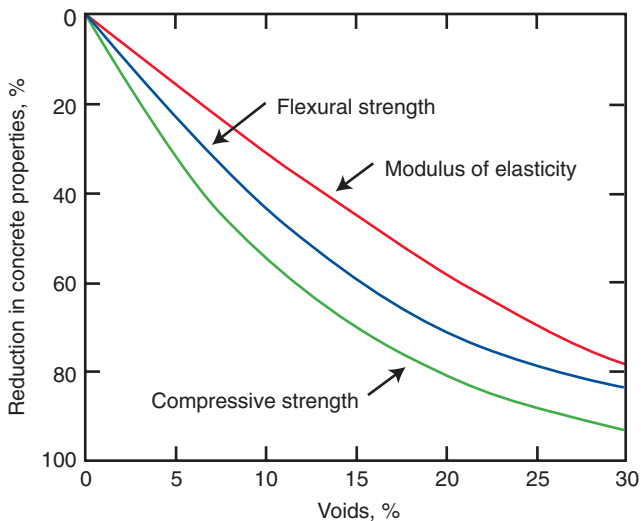


Fig. 1-9. Effect of voids in concrete due to a lack of consolidation on modulus of elasticity, compressive strength, and flexural strength.

## Hydration, Setting Time, and Hardening

The binding quality of portland cement paste is due to the chemical reaction between the cement and water, called hydration.

Portland cement is not a simple chemical compound, it is a mixture of many compounds. Four of these make up 90% or more of the weight of portland cement: tricalcium silicate, dicalcium silicate, tricalcium aluminate, and tetra-calcium aluminoferrite. In addition to these major compounds, several others play important roles in the hydration process. Each type of portland cement contains the same four major compounds, but in different proportions.

When clinker (the kiln product that is ground to make portland cement) is examined under a microscope, most of the individual cement compounds can be identified and their amounts determined. However, the smallest grains elude visual detection. The average diameter of a typical cement particle is approximately 15 micrometers. If all cement particles were average, portland cement would contain about 300 billion particles per kilogram, but in fact there are some 16,000 billion particles per kilogram because of the broad range of particle sizes. The particles in a kilogram of portland cement have a surface area of approximately 400 square meters.

The two calcium silicates, which constitute about 75% of the weight of portland cement, react with water to form two new compounds: calcium hydroxide and *calcium silicate hydrate*. The latter is by far the most important cementing component in concrete. The engineering properties of concrete—setting and hardening, strength, and dimensional stability—depend primarily on calcium silicate hydrate. It is the heart of concrete.

The chemical composition of calcium silicate hydrate is somewhat variable, but it contains lime (CaO) and silicate (SiO<sub>2</sub>) in a ratio on the order of 3 to 2. The surface area of calcium silicate hydrate is some 300 square meters per gram. In hardened cement paste, the calcium silicate hydrate forms dense, bonded aggregations between the other crystalline phases and the remaining unhydrated cement grains; they also adhere to grains of sand and to pieces of coarse aggregate, cementing everything together (Copeland and Schulz 1962).

As concrete hardens, its gross volume remains almost unchanged, but hardened concrete contains pores filled with water and air that have no strength. The strength is in the solid part of the paste, mostly in the calcium silicate hydrate and crystalline compounds.

The less porous the cement paste, the stronger the concrete. When mixing concrete, therefore, no more water than is absolutely necessary to make the concrete plastic and workable should be used. Even then, the water used is usually more than is required for complete hydration of the cement. About 0.4 grams of water per gram of cement are needed to completely hydrate cement (Powers 1948 and 1949). However, complete hydration is rare in field concrete due to a lack of moisture and the long period of time (decades) required to achieve complete hydration.

Knowledge of the amount of heat released as cement hydrates can be useful in planning construction. In winter, the heat of hydration will help protect the concrete against damage from freezing temperatures. The heat may be harmful, however, in massive structures such as dams because it may produce undesirable temperature differentials.

Knowledge of the rate of reaction between cement and water is important because it determines the rate of hardening. The initial reaction must be slow enough to allow time for the concrete to be transported and placed. Once the concrete has been placed and finished, however, rapid

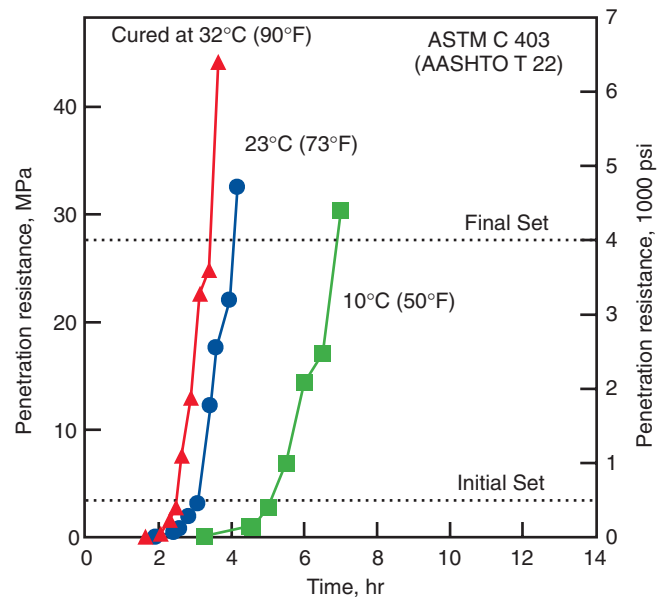


Fig. 1-11. Initial and final set times for a concrete mixture at different temperatures (Burg 1996).

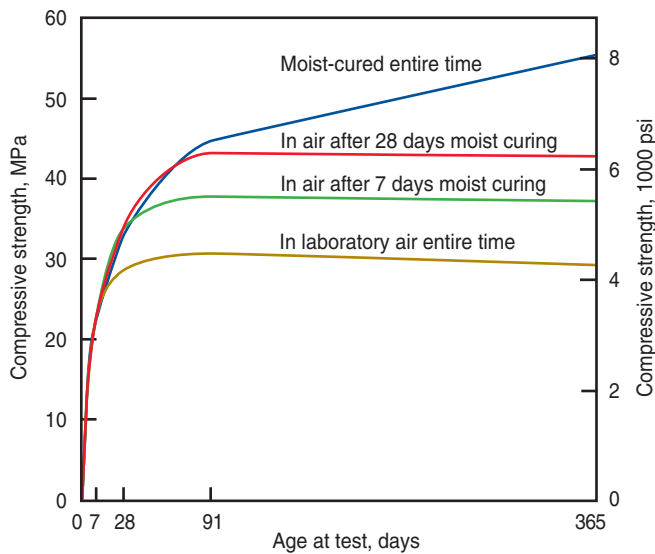
hardening is desirable. Gypsum, added at the cement mill when clinker is ground, acts as a regulator of the initial rate of setting of portland cement. Other factors that influence the rate of hydration include cement fineness, admixtures, amount of water added, and temperature of the materials at the time of mixing. Fig. 1-11 illustrates the setting properties of a concrete mixture at different temperatures.

## HARDENED CONCRETE

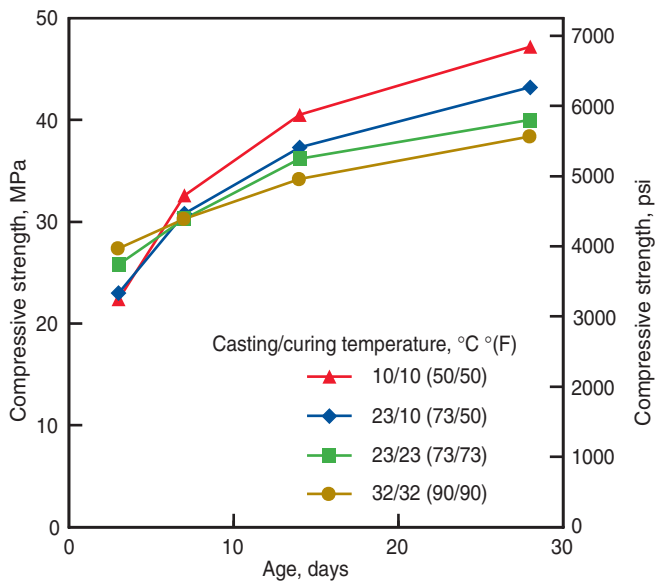
### Curing

Increase in strength with age continues provided (1) unhydrated cement is still present, (2) the concrete remains moist or has a relative humidity above approximately 80% (Powers 1948), (3) the concrete temperature remains favorable, and (4) sufficient space is available for hydration products to form. When the relative humidity within the concrete drops to about 80%, or the temperature of the concrete drops below freezing, hydration and strength gain virtually stop. Fig. 1-12 illustrates the relationship between strength gain and moist curing, while Fig. 1-13 illustrates the relationship between strength gain and curing temperature.

If concrete is resaturated after a drying period, hydration is resumed and strength will again increase. However, it is best to moist-cure concrete continuously from the time it is placed until it has attained the desired quality; once concrete has dried out it is difficult to resaturate. Fig. 1-14 illustrates the long-term strength gain of concrete in an outdoor exposure. Outdoor exposures often continue to provide moisture through ground contact and rainfall. Indoor concretes often dry out after curing and do not continue to gain strength (Fig. 1-12).



**Fig. 1-12. Concrete strength increases with age as long as moisture and a favorable temperature are present for hydration of cement (Gonnerman and Shuman 1928).**

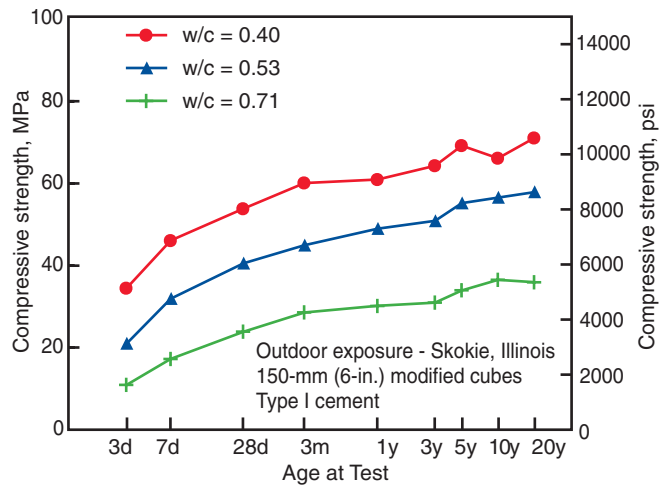


**Fig. 1-13. Effect of casting and curing temperature on strength development. Note that cooler temperatures result in lower early strength and higher later strength (Burg, 1996).**

### Drying Rate of Concrete

Concrete does not harden or cure by drying. Concrete (or more precisely, the cement in it) needs moisture to hydrate and harden. When concrete dries out, it ceases to gain strength; the fact that it is dry is no indication that it has undergone sufficient hydration to achieve the desired physical properties.

Knowledge of the rate of drying is helpful in understanding the properties or physical condition of concrete.



**Fig. 1-14. Concrete strength gain versus time for concrete exposed to outdoor conditions. Concrete continues to gain strength for many years when moisture is provided by rainfall and other environmental sources (Wood 1992).**

For example, as mentioned, concrete must continue to hold enough moisture throughout the curing period for the cement to hydrate to the extent that desired properties are achieved. Freshly cast concrete usually has an abundance of water, but as drying progresses from the surface inward, strength gain will continue at each depth only as long as the relative humidity at that point remains above 80%.

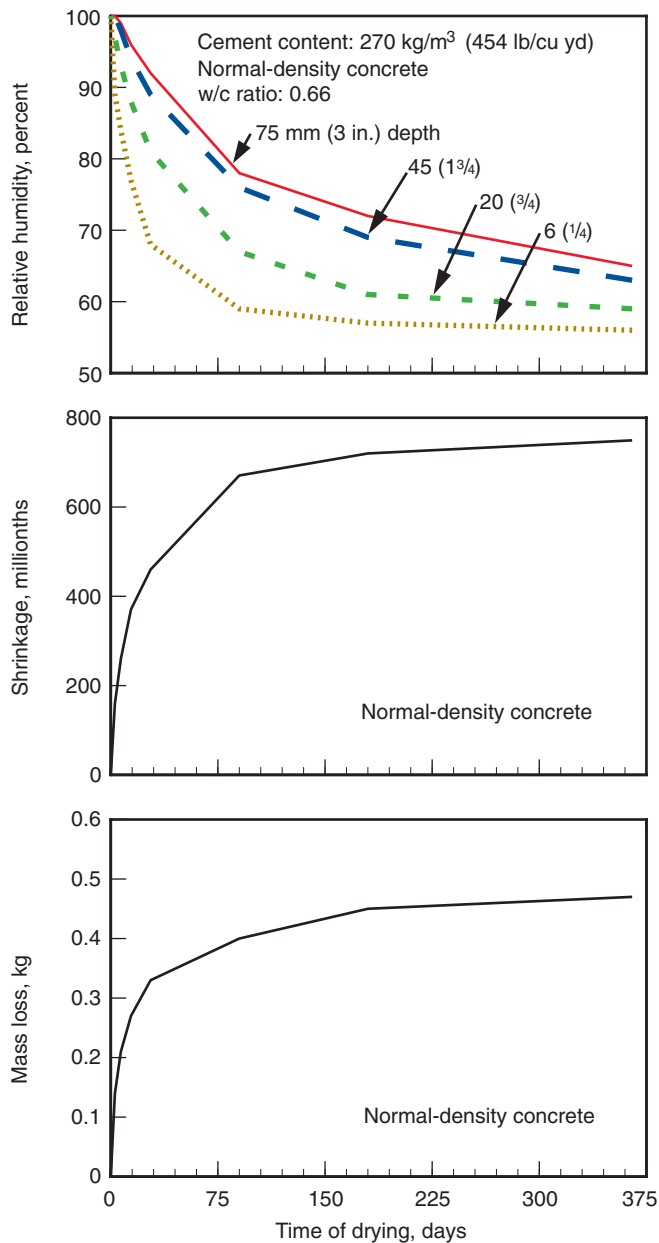
A common illustration of this is the surface of a concrete floor that has not had sufficient moist curing. Because it has dried quickly, concrete at the surface is weak and traffic on it creates dusting. Also, when concrete dries, it shrinks as it loses water (Fig. 1-15), just as wood and clay do (though not as much). Drying shrinkage is a primary cause of cracking, and the width of cracks is a function of the degree of drying, spacing or frequency of cracks, and the age at which the cracks occur.

While the surface of a concrete element will dry quite rapidly, it takes a much longer time for concrete in the interior to dry. Fig. 1-15 (top) illustrates the rate of drying at various depths within concrete cylinders exposed to laboratory air. Field concrete elements would have different drying profiles due to environmental conditions, size effects, and concrete properties.

The moisture content of concrete depends on the concrete's constituents, original water content, drying conditions, and the size of the concrete element (Heddenblad 1997 and 1998). After several months of drying in air with a relative humidity of 50% to 90%, moisture content is about 1% to 2% by mass of the concrete. Fig. 1-15 illustrates moisture loss and resulting shrinkage.

Size and shape of a concrete member have an important bearing on the rate of drying. Concrete elements with large surface area in relation to volume (such as floor slabs)





**Fig. 1-15. Relative humidity distribution, drying shrinkage, and mass loss of 150 x 300-mm (6 x 12-in.) cylinders moist cured for 7 days followed by drying in laboratory air at 23°C (73°F) (Hanson 1968).**

dry faster than voluminous concrete members with relatively small surface areas (such as bridge piers).

Many other properties of hardened concrete also are affected by its moisture content; these include elasticity, creep, insulating value, fire resistance, abrasion resistance, electrical conductivity, frost resistance, scaling resistance, and resistance to alkali-aggregate reactivity.

## Strength

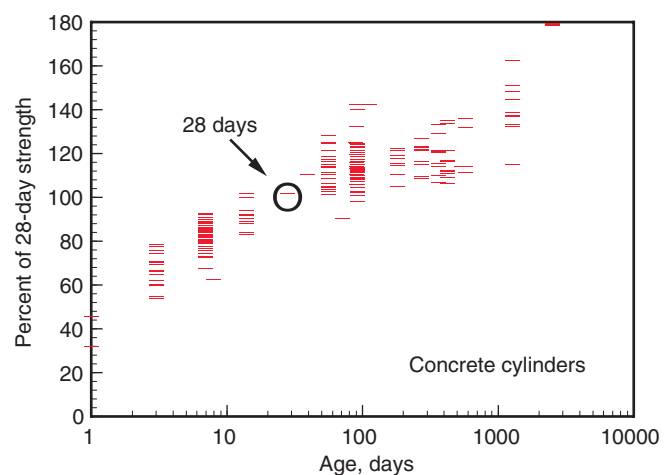
Compressive strength may be defined as the measured maximum resistance of a concrete specimen to axial load-

ing. It is generally expressed in megapascals (MPa) or pounds per square inch (psi) at an age of 28 days. One megapascal equals the force of one newton per square millimeter (N/mm<sup>2</sup>) or 1,000,000 N/m<sup>2</sup>. Other test ages are also used; however, it is important to realize the relationship between the 28-day strength and other test ages. Seven-day strengths are often estimated to be about 75% of the 28-day strength and 56-day and 90-day strengths are about 10% to 15% greater than 28-day strengths as shown in Fig. 1-16. The specified compressive strength is designated by the symbol  $f'_c$ , and ideally is exceeded by the actual compressive strength,  $f_c$ .

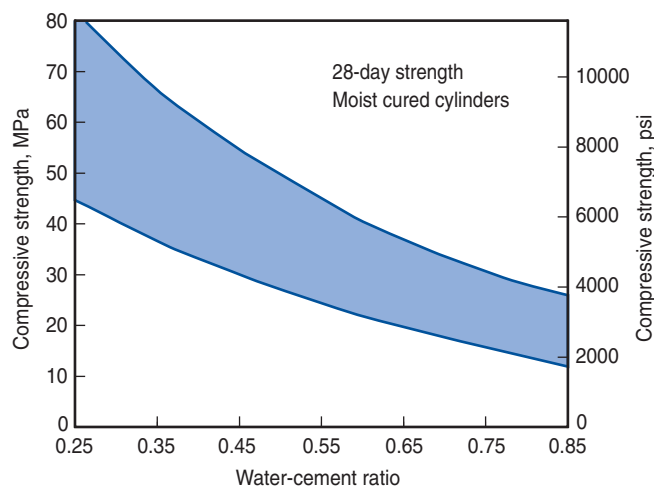
The compressive strength that a concrete achieves,  $f_c$ , results from the water-cement ratio (or water-cementitious materials ratio), the extent to which hydration has progressed, the curing and environmental conditions, and the age of the concrete. The relationship between strength and water-cement ratio has been studied since the late 1800s and early 1900s (Feret 1897 and Abrams 1918). Fig. 1-17 shows compressive strengths for a wide range of concrete mixtures and water-cement ratios at an age of 28 days. Note that strengths increase as the water-cement ratios decrease. These factors also affect flexural and tensile strengths and bond of concrete to steel.

The water-cement ratio compressive strength relationships in Fig. 1-17 are for typical non-air-entrained concretes. When more precise values for concrete are required, graphs should be developed for the specific materials and mix proportions to be used on the job.

For a given workability and a given amount of cement, air-entrained concrete requires less mixing water than non-air-entrained concrete. The lower water-cement ratio possible for air-entrained concrete tends to offset the somewhat lower strengths of air-entrained concrete, particularly in lean to medium cement content mixes.



**Fig. 1-16. Compressive strength development of various concretes illustrated as a percentage of the 28-day strength (Lange 1994).**



**Fig. 1-17. Range of typical strength to water-cement ratio relationships of portland cement concrete based on over 100 different concrete mixtures cast between 1985 and 1999.**

To determine compressive strength, tests are made on specimens of mortar or concrete; in the United States, unless otherwise specified, compression tests of mortar are made on 50-mm (2-in.) cubes, while compression tests of concrete are made on cylinders 150 mm (6 in.) in diameter and 300 mm (12 in.) high (see Fig. 1-18). Smaller cylinders, 100 x 200 mm (4 x 8 in.) are also used for concrete.

Compressive strength of concrete is a primary physical property and frequently used in design calculations for bridges, buildings, and other structures. Most general-use concrete has a compressive strength between 20 and 40 MPa (3000 and 6000 psi). Compressive strengths of 70 to 140 MPa (10,000 to 20,000 psi) have been used in special bridge and high-rise building applications.

The flexural strength or modulus of rupture of concrete is used to design pavements and other slabs on ground. Compressive strength, which is easier to measure than flexural strength, can be used as an index of flexural strength, once the empirical relationship between them has been established for the materials and the size of the element involved. The flexural strength of normal-weight concrete is often approximated as 0.7 to 0.8 times the square root of the compressive strength in megapascals (7.5 to 10 times the square root of the compressive strength in pounds per square inch). Wood (1992) illustrates the relationship between flexural strength and compressive strength for concretes exposed to moist curing, air curing, and outdoor exposure.

The direct tensile strength of concrete is about 8% to 12% of the compressive strength and is often estimated as 0.4 to 0.7 times the square root of the compressive strength in megapascals (5 to 7.5 times the square root of the compressive strength in pounds per square inch). Splitting tensile strength is 8% to 14% of the compressive strength (Hanson 1968). Splitting tensile strength versus time is presented by Lange (1994).



**Fig. 1-18. Testing a 150 x 300-mm (6 x 12-in.) concrete cylinder in compression. The load on the test cylinder is registered on the display. (68959)**

The torsional strength for concrete is related to the modulus of rupture and the dimensions of the concrete element. Hsu (1968) presents torsional strength correlations.

Shear strength–compressive strength relationships are discussed in the ACI 318 building code. The correlation between compressive strength and flexural, tensile, torsional, and shear strength varies with concrete ingredients and environment.

Modulus of elasticity, denoted by the symbol  $E$ , may be defined as the ratio of normal stress to corresponding strain for tensile or compressive stresses below the proportional limit of a material. For normal-weight concrete,  $E$  ranges from 14,000 to 41,000 MPa (2 to 6 million psi) and can be approximated as 5,000 times the square root of the compressive strength in megapascals (57,000 times the square root of the compressive strength in pounds per square inch). Like other strength relationships, the modulus of elasticity to compressive strength relationship is mix-ingredient specific and should be verified in a laboratory (Wood 1992).

## Density

Conventional concrete, normally used in pavements, buildings, and other structures, has a density (unit weight) in the range of 2200 to 2400 kg/m<sup>3</sup> (137 to 150 lb/ft<sup>3</sup>). The density of concrete varies, depending on the amount and density of the aggregate, the amount of air that is entrapped or purposely entrained, and the water and cement contents, which in turn are influenced by the maximum size of the aggregate. Reducing the cement paste content (increasing aggregate volume) increases density. Values of the density of fresh concrete are given in Table 1-1. In the design of reinforced concrete structures, the combination of conventional concrete and reinforcing steel is commonly assumed to weigh 2400 kg/m<sup>3</sup> (150 lb/ft<sup>3</sup>).



**Table 1-1. Observed Average Density of Fresh Concrete (SI Units)\***

| Maximum size of aggregate, mm | Air content, percent | Water, kg/m <sup>3</sup> | Cement, kg/m <sup>3</sup> | Density, kg/m <sup>3**</sup>   |      |      |      |      |
|-------------------------------|----------------------|--------------------------|---------------------------|--------------------------------|------|------|------|------|
|                               |                      |                          |                           | Relative density of aggregate† |      |      |      |      |
|                               |                      |                          |                           | 2.55                           | 2.60 | 2.65 | 2.70 | 2.75 |
| 19                            | 6.0                  | 168                      | 336                       | 2194                           | 2227 | 2259 | 2291 | 2323 |
| 37.5                          | 4.5                  | 145                      | 291                       | 2259                           | 2291 | 2339 | 2371 | 2403 |
| 75                            | 3.5                  | 121                      | 242                       | 2307                           | 2355 | 2387 | 2435 | 2467 |

\* Source: Bureau of Reclamation 1981, Table 4.

\*\* Air-entrained concrete with indicated air content.

† On saturated surface-dry basis. Multiply relative density by 1000 to obtain density of aggregate particles in kg/m<sup>3</sup>.

**Table 1-1. Observed Average Density of Fresh Concrete (Inch-Pound Units)\***

| Maximum size of aggregate, in. | Air content, percent | Water, lb/yd <sup>3</sup> | Cement, lb/yd <sup>3</sup> | Density, lb/ft <sup>3**</sup>  |      |      |      |      |
|--------------------------------|----------------------|---------------------------|----------------------------|--------------------------------|------|------|------|------|
|                                |                      |                           |                            | Specific gravity of aggregate† |      |      |      |      |
|                                |                      |                           |                            | 2.55                           | 2.60 | 2.65 | 2.70 | 2.75 |
| ¾                              | 6.0                  | 283                       | 566                        | 137                            | 139  | 141  | 143  | 145  |
| 1½                             | 4.5                  | 245                       | 490                        | 141                            | 143  | 146  | 148  | 150  |
| 3                              | 3.5                  | 204                       | 408                        | 144                            | 147  | 149  | 152  | 154  |

\* Source: Bureau of Reclamation 1981, Table 4.

\*\* Air-entrained concrete with indicated air content.

† On saturated surface-dry basis. Multiply specific gravity by 62.4 to obtain density of aggregate particles in lb/ft<sup>3</sup>.

The weight of dry concrete equals the weight of the freshly mixed concrete ingredients less the weight of mix water that evaporates into the air. Some of the mix water combines chemically with the cement during the hydration process, converting the cement into cement gel. Also, some of the water remains tightly held in pores and capillaries and does not evaporate under normal conditions. The amount of mix water that will evaporate from concrete exposed to ambient air at 50% relative humidity is about ½% to 3% of the concrete weight; the actual amount depends on initial water content of the concrete, absorption characteristics of the aggregates, and size and shape of the concrete element.

Aside from conventional concrete, there is a wide spectrum of special concretes to meet various needs; they range from lightweight insulating concretes with a density of as little as 240 kg/m<sup>3</sup> (15 lb/ft<sup>3</sup>) to heavyweight concrete with a density of up to 6000 kg/m<sup>3</sup> (375 lb/ft<sup>3</sup>) used for counterweights or radiation shielding.

## Permeability and Watertightness

Concrete used in water-retaining structures or exposed to weather or other severe exposure conditions must be virtually impermeable or watertight. Watertightness is often referred to as the ability of concrete to hold back or retain water without visible leakage. Permeability refers to the amount of water migration through concrete when the water is under pressure or to the ability of concrete to resist

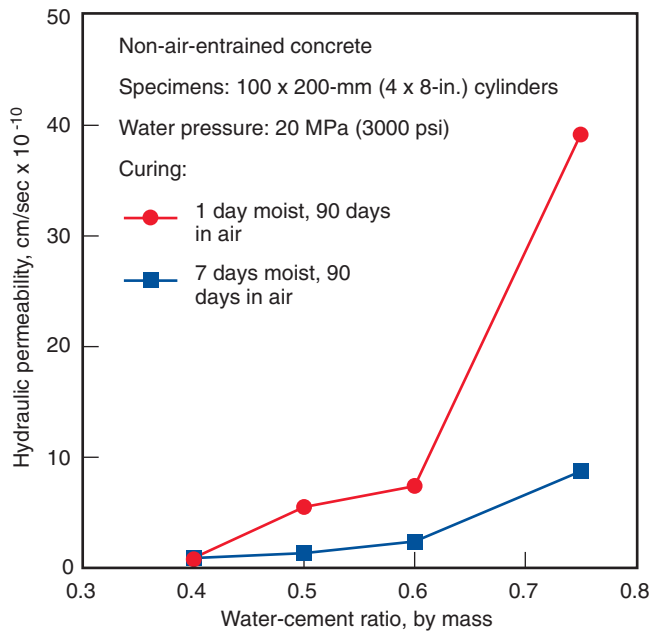
penetration by water or other substances (liquid, gas, or ions). Generally, the same properties of concrete that make it less permeable also make it more watertight.

The overall permeability of concrete to water is a function of: (1) the permeability of the paste; (2) the permeability and gradation of the aggregate; (3) the quality of the paste and aggregate transition zone; and (4) the relative proportion of paste to aggregate. Decreased permeability improves concrete's resistance to freezing and thawing, resaturation, sulfate, and chloride-ion penetration, and other chemical attack.

The permeability of the paste is particularly important because the paste envelops all constituents in the concrete. Paste permeability is related to water-cement ratio, degree of cement hydration, and length of moist curing. A low-permeability concrete requires a low water-cement ratio and an adequate moist-curing period. Air entrainment aids watertightness but has little effect on permeability. Permeability increases with drying.

The permeability of mature hardened cement paste kept continuously moist ranges from  $0.1 \times 10^{-12}$  to  $120 \times 10^{-12}$  cm per sec. for water-cement ratios ranging from 0.3 to 0.7 (Powers and others 1954). The permeability of rock commonly used as concrete aggregate varies from approximately  $1.7 \times 10^{-9}$  to  $3.5 \times 10^{-13}$  cm per sec. The permeability of mature, good-quality concrete is approximately  $1 \times 10^{-10}$  cm per sec.

The relationship between permeability, water-cement ratio, and initial curing for 100 x 200-mm (4 x 8-in.) cylindrical concrete specimens tested after 90 days of air drying



**Fig. 1-19. Relationship between hydraulic (water) permeability, water-cement ratio, and initial curing on concrete specimens (Whiting 1989).**

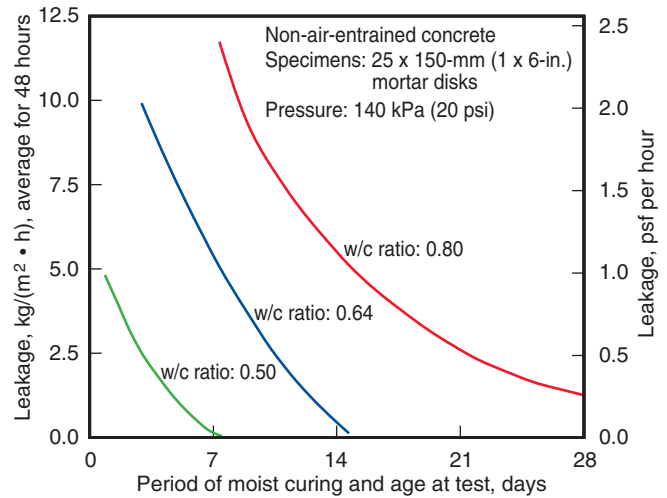
and subjected to 20 MPa (3000 psi) of water pressure is illustrated in Fig. 1-19. Although permeability values would be different for other liquids and gases, the relationship between water-cement ratio, curing period, and permeability would be similar.

Test results obtained by subjecting 25-mm (1-in.) thick non-air-entrained mortar disks to 140-kPa (20-psi) water pressure are given in Fig. 1-20. In these tests, there was no water leakage through mortar disks that had a water-cement ratio of 0.50 by weight or less and were moist-cured for seven days. Where leakage occurred, it was greater in mortar disks made with high water-cement ratios. Also, for each water-cement ratio, leakage was less as the length of the moist-curing period increased. In disks with a water-cement ratio of 0.80, the mortar still permitted leakage after being moist-cured for one month. These results clearly show that a low water-cement ratio and a reasonable period of moist curing significantly reduce permeability.

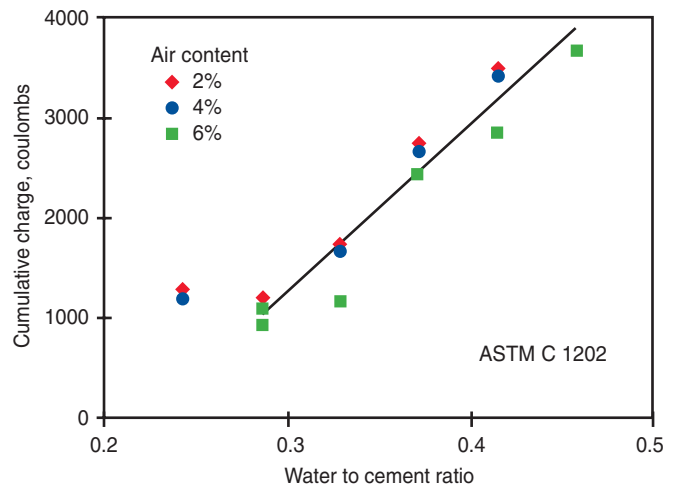
Fig. 1-21 illustrates the effect of different water to cement ratios on concrete's resistance to chloride ion penetration as indicated by electrical conductance. The total charge in coulombs was significantly reduced with a low water to cement ratio. Also, the results showed that a lower charge passed when the concrete contained a higher air content.

A low water-cement ratio also reduces segregation and bleeding, further contributing to watertightness. Of course watertight concrete must also be free from cracks, honeycomb, or other large visible voids.

Occasionally, pervious concrete—no-fines concrete that readily allows passage of water—is designed for special applications. In these concretes, the fine aggregate is



**Fig. 1-20. Effect of water-cement ratio (w/c) and curing duration on permeability of mortar. Note that leakage is reduced as the water-cement ratio is decreased and the curing period increased (McMillan and Lyse 1929 and PCA Major Series 227).**



**Fig. 1-21. Total charge at the end of the rapid chloride permeability test as a function of water to cement ratio (Pinto and Hover 2001).**

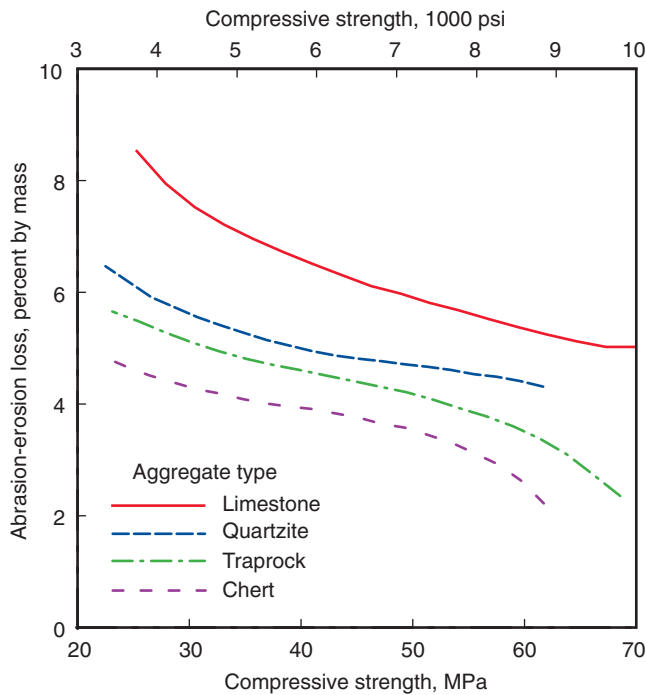
greatly reduced or completely removed, producing a high volume of air voids. Pervious concrete has been used in tennis courts, pavements, parking lots, greenhouses, and drainage structures. Pervious concrete has also been used in buildings because of its thermal insulation properties.

### Abrasion Resistance

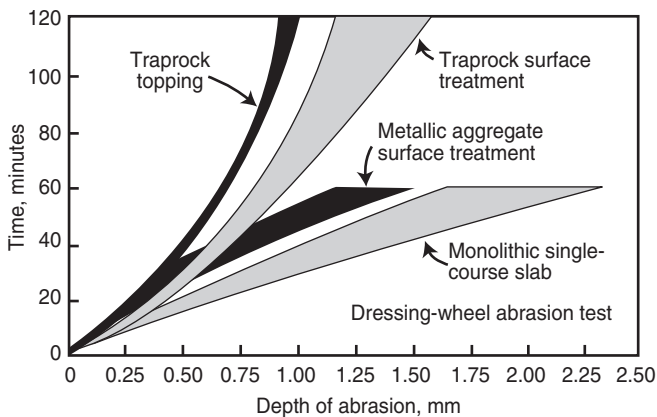
Floors, pavements, and hydraulic structures are subjected to abrasion; therefore, in these applications concrete must have a high abrasion resistance. Test results indicate that abrasion resistance is closely related to the compressive strength of concrete. Strong concrete has more resistance to

abrasion than does weak concrete. Since compressive strength depends on water-cement ratio and curing, a low water-cement ratio and adequate curing are necessary for abrasion resistance. The type of aggregate and surface finish or treatment used also have a strong influence on abrasion resistance. Hard aggregate is more wear resistant than soft aggregate and a steel-troweled surface resists abrasion better than a surface that had not been troweled.

Fig. 1-22 shows results of abrasion tests on concretes of different compressive strengths and aggregate types. Fig. 1-23 illustrates the effect hard steel troweling and surface



**Fig. 1-22. Effect of compressive strength and aggregate type on the abrasion resistance of concrete (ASTM C 1138). High-strength concrete made with a hard aggregate is highly resistant to abrasion (Liu 1981).**



**Fig. 1-23. Effect of hard steel troweling and surface treatments on the abrasion resistance of concrete (ASTM C 779). Base slab compressive strength was 40 MPa (6000 psi) at 28 days. All slabs were steel troweled (Brinkerhoff 1970).**

treatments, such as metallic or mineral aggregate surface hardeners, have on abrasion resistance. Abrasion tests can be conducted by rotating steel balls, dressing wheels, or disks under pressure over the surface (ASTM C 779). One type of test apparatus is pictured in Fig. 1-24. Other types of abrasion tests are also available (ASTM C 418 and C 944).

## Volume Stability and Crack Control

Hardened concrete changes volume due to changes in temperature, moisture, and stress. These volume or length changes may range from about 0.01% to 0.08%. Thermal volume changes of hardened concrete are about the same as those for steel.

Concrete under stress will deform elastically. Sustained stress will result in additional deformation called creep. The rate of creep (deformation per unit of time) decreases with time.

Concrete kept continually moist will expand slightly. When permitted to dry, concrete will shrink. The primary factor influencing the amount of drying shrinkage is the water content of the freshly mixed concrete. Drying shrinkage increases directly with increases in this water content. The amount of shrinkage also depends upon several other



**Fig. 1-24. Test apparatus for measuring abrasion resistance of concrete. The machine can be adjusted to use either revolving disks or dressing wheels. With a different machine, steel balls under pressure are rolled over the surface of the specimen. The tests are described in ASTM C 779. (44015)**



factors, such as: (1) the amount of aggregate used; (2) properties of the aggregate; (3) size and shape of the concrete element; (4) relative humidity and temperature of the ambient air; (5) method of curing; (6) degree of hydration; and (7) time.

Two basic causes of cracks in concrete are: (1) stress due to applied loads and (2) stress due to drying shrinkage or temperature changes when concrete is restrained.

Drying shrinkage is an inherent, unavoidable property of concrete; therefore, properly positioned reinforcing steel is used to reduce crack widths, or joints are used to pre-determine and control the location of cracks. Thermal stress due to fluctuations in ambient temperature also can cause cracking, particularly at an early age.

Concrete shrinkage cracks can occur because of restraint. When drying shrinkage occurs and there is no restraint, the concrete does not crack. Restraint comes from several sources. Drying shrinkage is always greater near the surface of concrete; the moist inner portions restrain the concrete near the surface, which can cause cracking. Other sources of restraint are reinforcing steel embedded in concrete, the interconnected parts of a concrete structure, and the friction of the subgrade on which concrete is placed.

**Joints.** Joints are the most effective method of controlling unsightly cracking. If a sizable expanse of concrete (a wall, slab, or pavement) is not provided with properly spaced joints to accommodate drying shrinkage and temperature contraction, the concrete will crack in a random manner.

Contraction (shrinkage control) joints are grooved, formed, or sawed into sidewalks, driveways, pavements, floors, and walls so that cracking will occur in these joints rather than in a random manner. Contraction joints permit movement in the plane of a slab or wall. They extend to a depth of approximately one-quarter the concrete thickness.

Isolation joints separate a concrete placement from other parts of a structure and permit horizontal and vertical movements. They should be used at the junction of floors with walls, columns, footings, and other points where restraint can occur. They extend the full depth of slabs and include a premolded joint filler.

Construction joints occur where concrete work is concluded for the day; they separate areas of concrete placed at different times. In slabs-on-ground, construction joints usually align with, and function as, control or isolation joints. They may require dowels for load transfer.

of those ingredients, interactions between the ingredients, and placing and curing practices determine the ultimate durability and life of the concrete.

## Resistance to Freezing and Thawing

Concrete used in structures and pavements is expected to have long life and low maintenance. It must have good durability to resist anticipated exposure conditions. The most potentially destructive weathering factor is freezing and thawing while the concrete is wet, particularly in the presence of deicing chemicals. Deterioration is caused by the freezing of water and subsequent expansion in the paste, the aggregate particles, or both.

With air entrainment, concrete is highly resistant to this type of deterioration as shown in Fig. 1-25. During freezing, the water displaced by ice formation in the paste is accommodated so that it is not disruptive; the microscopic air bubbles in the paste provide chambers for the water to enter and thus relieve the hydraulic pressure generated.

When freezing occurs in concrete containing saturated aggregate, disruptive hydraulic pressures can also be generated within the aggregate. Water displaced from the aggregate particles during the formation of ice cannot escape fast enough to the surrounding paste to relieve pressure. However, under most exposure conditions, a good-quality paste (low water-cement ratio) will prevent most aggregate particles from becoming saturated. Also, if the paste is air-entrained, it will accommodate the small amounts of excess water that may be expelled from aggregates, thus protecting the concrete from freeze-thaw damage.

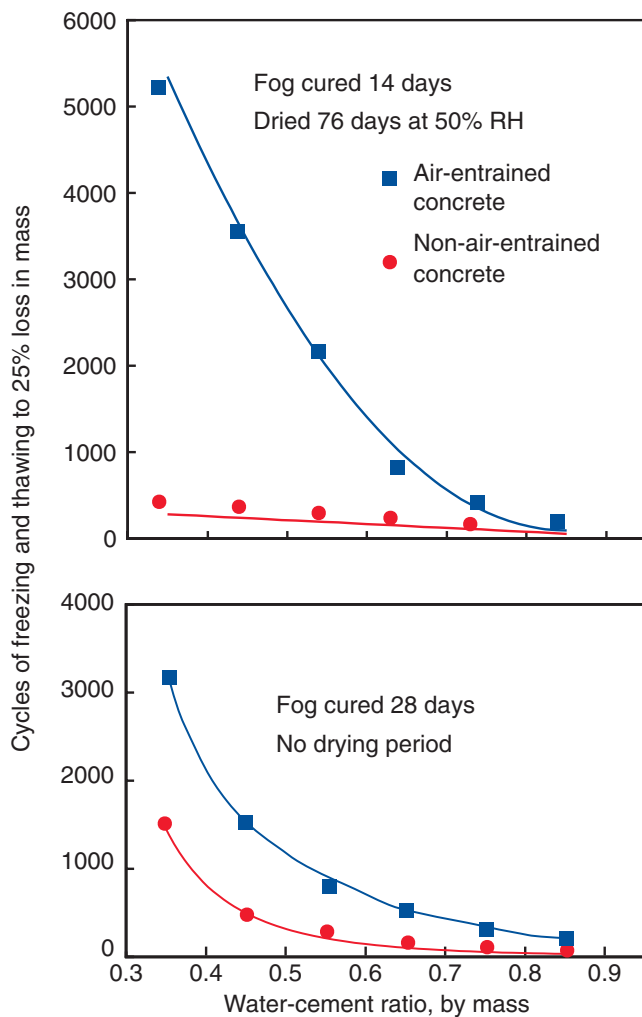
Fig. 1-26 illustrates, for a range of water-cement ratios, that (1) air-entrained concrete is much more resistant to freeze-thaw cycles than non-air-entrained concrete, (2) concrete with a low water-cement ratio is more durable than

## Video DURABILITY

The durability of concrete may be defined as the ability of concrete to resist weathering action, chemical attack, and abrasion while maintaining its desired engineering properties. Different concretes require different degrees of durability depending on the exposure environment and the properties desired. The concrete ingredients, proportioning



Fig. 1-25. Air-entrained concrete (bottom bar) is highly resistant to repeated freeze-thaw cycles. (P25542)



**Fig. 1-26. Relationship between freeze-thaw resistance, water-cement ratio, and drying for air-entrained and non-air-entrained concretes made with Type I cement. High resistance to freezing and thawing is associated with entrained air, low water-cement ratio, and a drying period prior to freeze-thaw exposure (Backstrom and others 1955).**

concrete with a high water-cement ratio, and (3) a drying period prior to freeze-thaw exposure substantially benefits the freeze-thaw resistance of air-entrained concrete. Air-entrained concrete with a low water-cement ratio and an air content of 5% to 8% will withstand a great number of cycles of freezing and thawing without distress (Woods 1956).

Freeze-thaw durability can be determined by laboratory test procedure ASTM C 666, *Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing* (AASHTO T 161). From the test, a durability factor is calculated that reflects the number of cycles of freezing and thawing required to produce a certain amount of deterioration. Deicer-scaling resistance can be determined by ASTM C 672, *Standard Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals*.

## Alkali-Aggregate Reactivity

Alkali-aggregate reactivity is a type of concrete deterioration that occurs when the active mineral constituents of some aggregates react with the alkali hydroxides in the concrete. The reactivity is potentially harmful only when it produces significant expansion. Alkali-aggregate reactivity occurs in two forms—alkali-silica reaction (ASR) and alkali-carbonate reaction (ACR). Alkali-silica reaction is of more concern than alkali-carbonate reaction because the occurrence of aggregates containing reactive silica minerals is more common.

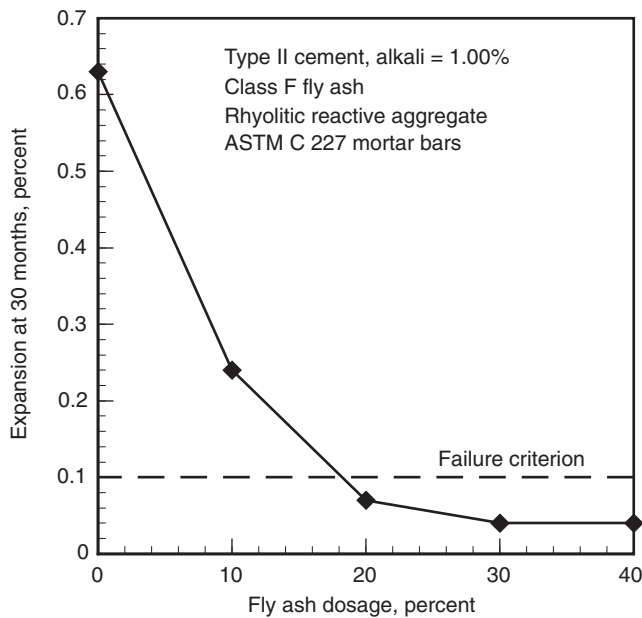
Indications of the presence of alkali-aggregate reactivity may be a network of cracks, closed or spalling joints, or displacement of different portions of a structure (Fig. 1-27). Because deterioration due to alkali-aggregate reaction is a slow process, the risk of catastrophic failure is low. Alkali-aggregate reaction can cause serviceability problems and exacerbate other deterioration mechanisms, such as those that occur in frost, deicer, or sulfate exposures.

Current practices to control alkali-silica reactivity include the use of supplementary cementitious materials or blended cements proven by testing to control the reaction. Supplementary cementitious materials include fly ash, ground granulated blast-furnace slag, silica fume, and natural pozzolans (Fig. 1-28). Blended cements also contain these materials to control alkali-silica reactivity. This practice allows the use of locally available aggregates and cementitious materials. Reduction of the alkali content of the concrete can also control the reaction.

Use of supplementary cementitious materials or blended cements does not control alkali-carbonate reaction. Fortunately this reaction is rare. If aggregate testing indicates that an aggregate is susceptible to alkali-carbonate reactivity, the reaction can be controlled through the use of selective quarrying, aggregate blending, reducing maximum aggregate size, or using special chemical compounds that inhibit the reaction.



**Fig. 1-27. Cracking, joint closing, spalling, and lateral offset are caused by severe alkali-silica reactivity in this parapet wall. (56586)**



**Fig. 1-28.** Certain fly ashes at appropriate dosages can control alkali-silica reactivity.

See Farny and Kosmatka (1997) for more information on alkali-silica reaction and alkali-carbonate reaction.

## Carbonation

Carbonation of concrete is a process by which carbon dioxide in the ambient air penetrates the concrete and reacts with the hydroxides, such as calcium hydroxide, to form carbonates (Verbeck 1958). In the reaction with calcium hydroxide, calcium carbonate is formed. Carbonation and rapid drying of fresh concrete may affect surface durability, but this is prevented by proper curing. Carbonation of hardened concrete does not harm the concrete matrix. However, carbonation significantly lowers the alkalinity (pH) of the concrete. High alkalinity is needed to protect embedded steel from corrosion; consequently, concrete should be resistant to carbonation to help prevent steel corrosion.

The amount of carbonation is significantly increased in concrete that has a high water to cement ratio, low cement content, short curing period, low strength, and highly permeable (porous) paste. The depth of carbonation in good-quality, well-cured concrete is generally of little practical significance as long as embedded steel has adequate concrete cover (Fig. 1-29). Finished surfaces tend to have less carbonation than formed surfaces. Carbonation of finished surfaces is often observed to a depth of 1 to 10 mm (0.04 to 0.4 in.) and for formed surfaces, between 2 and 20 mm (0.1 and 0.9 in.) after several years of exposure, depending on the concrete properties, ingredients, age, and environmental exposure (Campbell, Sturm, and Kosmatka 1991). ACI 201.2R, *Guide to Durable Concrete*, has more information on atmospheric and water carbonation and the



**Fig. 1-29.** Carbonation destroys concrete's ability to protect embedded steel from corrosion. All concrete carbonates to a small depth, but reinforcing steel must have adequate concrete cover to prevent carbonation from reaching the steel. This reinforcing bar in a wall had less than 10 mm (0.4 in.) of concrete cover; the ACI building code requires a minimum of 38 mm (1½ in.). After years of outdoor exposure, the concrete carbonated to the depth of the bar, allowing the steel to rust and spall the concrete surface. (68340)

ACI 318 building code, provides reinforcing steel cover requirements for different exposures.

## Chloride Resistance and Steel Corrosion

Concrete protects embedded steel from corrosion through its highly alkaline nature. The high pH environment in concrete (usually greater than 12.5) causes a passive and noncorroding protective oxide film to form on steel. However, the presence of chloride ions from deicers or seawater can destroy or penetrate the film. Once the chloride corrosion threshold (about 0.15% water-soluble chloride by mass of cement) is reached, an electric cell is formed along the steel or between steel bars and the electrochemical process of corrosion begins. Some steel areas along the bar become the anode, discharging current in the electric cell; from there the iron goes into solution. Steel areas that receive current are the cathodes where hydroxide ions are formed. The iron and hydroxide ions form iron hydroxide, Fe(OH)<sub>2</sub>, which further oxidizes to form rust (iron oxide). Rusting is an expansive process—rust expands up to four times its original volume—which induces internal stress and eventual spalling of the concrete over reinforcing steel. The cross-sectional area of the steel can also be significantly reduced.

Once it starts, the rate of steel corrosion is influenced by the concrete's electrical resistivity, moisture content, and the rate at which oxygen migrates through the concrete to the steel. Chloride ions alone can also penetrate the passive film



on the reinforcement; they combine with iron ions to form a soluble iron chloride complex that carries the iron into the concrete for later oxidation (rust) (Whiting 1997, Taylor, Whiting, and Nagi 2000 and Whiting, Taylor and Nagi 2002).

The resistance of concrete to chloride is good; however, it can be increased by using a low water-cement ratio (0.40), at least seven days of moist curing, and supplementary cementitious materials, such as silica fume, to reduce permeability. Increasing the concrete cover over the steel also helps slow down the migration of chlorides.

Other methods of reducing steel corrosion include the use of corrosion inhibiting admixtures, epoxy-coated reinforcing steel (ASTM D 3963 or AASHTO M 284), surface treatments, concrete overlays, and cathodic protection.

Epoxy-coated reinforcing steel works by preventing chloride ions from reaching the steel (Fig. 1-30). Surface treatments and concrete overlays attempt to stop or reduce chloride ion penetration at the concrete surface. Silanes, siloxanes, methacrylates, epoxies, and other materials are used as surface treatments.

Impermeable materials, such as most epoxies, should not be used on slabs on ground or other concrete where moisture can freeze under the coating. The freezing water can cause surface delamination under the impermeable coating. Latex-modified portland cement concrete, low-slump concrete, and concrete with silica fume are used in overlays to reduce chloride-ion ingress.

Cathodic protection methods reverse the corrosion current flow through the concrete and reinforcing steel. This is done by inserting a nonstructural anode in the concrete and forcing the steel to be the cathode by electrically charging the system. The anode is connected to the positive pole of a rectifier. Since corrosion occurs where the current leaves the steel, the steel cannot corrode if it is receiving the induced current.

Chloride present in plain concrete (not containing steel) is generally not a durability concern.

Corrosion of nonferrous metals in concrete is discussed by Kerkhoff (2001).



Fig. 1-30. Epoxy-coated reinforcing steel used in a bridge deck. (69915)

## Chemical Resistance

Portland cement concrete is resistant to most natural environments; however, concrete is sometimes exposed to substances that can attack and cause deterioration. Concrete in chemical manufacturing and storage facilities is especially prone to chemical attack. The effect of sulfates and chlorides is discussed in this chapter. Acids attack concrete by dissolving cement paste and calcareous aggregates. In addition to using concrete with a low permeability, surface treatments can be used to keep aggressive substances from coming in contact with concrete. *Effects of Substances on Concrete and Guide to Protective Treatments* (Kerkhoff 2001) discusses the effects of hundreds of chemicals on concrete and provides a list of treatments to help control chemical attack.

## Sulfate Attack

Excessive amounts of sulfates in soil or water can attack and destroy a concrete that is not properly designed. Sulfates (for example calcium sulfate, sodium sulfate, and magnesium sulfate) can attack concrete by reacting with hydrated compounds in the hardened cement paste. These reactions can induce sufficient pressure to disrupt the cement paste, resulting in disintegration of the concrete (loss of paste cohesion and strength). Calcium sulfate attacks calcium aluminate hydrate and forms ettringite. Sodium sulfate reacts with calcium hydroxide and calcium aluminate hydrate forming ettringite and gypsum. Magnesium sulfate attacks in a manner similar to sodium sulfate and forms ettringite, gypsum, and also brucite (magnesium hydroxide). Brucite forms primarily on the concrete surface; it consumes calcium hydroxide, lowers the pH of the pore solution, and then decomposes the calcium silicate hydrates (Santhanam and others 2001).

Thaumasite may form during sulfate attack in moist conditions at temperatures usually between 0°C and 10°C (32°F to 50°F) and it occurs as a result of a reaction between calcium silicate hydrate, sulfate, calcium carbonate, and water (Report of the Thaumasite Expert Group 1999). In concretes where deterioration is associated with excess thaumasite formation, cracks can be filled with thaumasite and haloes of white thaumasite are present around aggregate particles. At the concrete/soil interface the surface concrete layer can be “mushy” with complete replacement of the cement paste by thaumasite (Hobbs 2001).

Like natural rock formations such as limestone, porous concrete is susceptible to weathering caused by salt crystallization. These salts may or may not contain sulfates and they may or may not react with the hydrated compounds in concrete. Examples of salts known to cause weathering of field concrete include sodium carbonate and sodium sulfate (laboratory studies have also related saturated solutions of calcium chloride and other salts to concrete deterioration). The greatest damage occurs with drying of saturated solutions of these salts, often in an environment with specific cyclic changes in relative humidity and temperature that alter mineralogical phases. In permeable concrete exposed to drying conditions, salt solutions

can rise to the surface by capillary action and subsequently—as a result of surface evaporation—the solution phase becomes supersaturated and salt crystallization occurs, sometimes generating pressures large enough to cause cracking. If the rate of migration of the salt solution through the pores is lower than the rate of evaporation, a drying zone forms beneath the surface and salt crystallization occurs in the pores causing expansion and scaling (Mehta 2000). Both aggregate particles and cement paste can be attacked by salts.

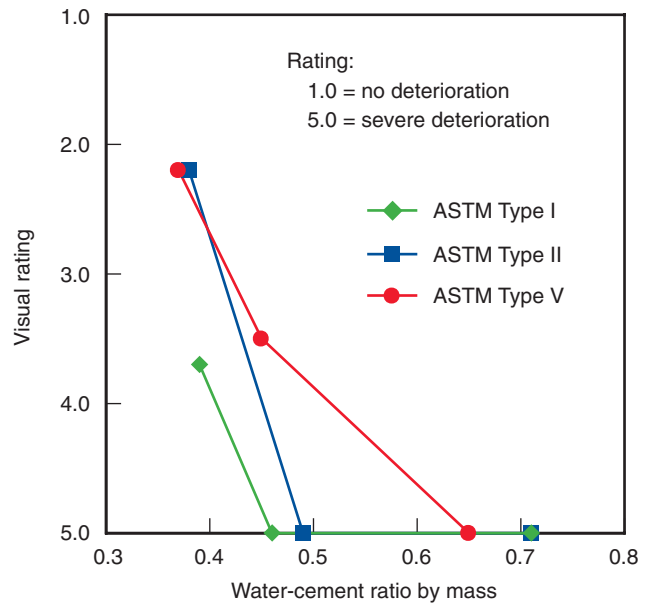


**Fig. 1-31. Sulfate attack is often the most severe at the location of the most wetting and drying, which is usually near the soil line. Here concrete posts have been attacked by sulfates near the soil line. Also see the inset in Fig. 1-32. The concrete is in better condition deep within the soil where it is moist. (43093)**

Sulfate attack and salt crystallization are more severe at locations where the concrete is exposed to wetting and drying cycles, than continuously wet exposures. This is often seen in concrete posts where the concrete has deteriorated only a few centimeters above and below the soil line (where it is continuously wet) is in good condition (Fig. 1-31 and 1-32). However, if the sulfate exposure is severe enough, with time even

the continuously moist sections can be attacked by sulfates if the concrete is not properly designed.

For the best defense against external sulfate attack: (1) design concrete with a low water to cementitious materials ratio (around 0.4), and (2) use cements specially formulated for sulfate environments, such as ASTM C 150 (AASHTO M 85) Type II or V cements, C 595 (AASHTO M 240) moderate sulfate resistant cements, or C 1157 Types MS or HS. The superior sulfate resistance of ASTM C 150 Type II and V cements is shown in Fig. 1-33.



**Fig. 1-33. Average 16-yr ratings of concrete beams in sulfate soils for three portland cements at various water-cement ratios (Stark 2002).**



**Fig. 1-32. Concrete beams after seven years of exposure to sulfate-rich wet soil in a Sacramento, California, test plot. The beams in better condition have low water-cementitious materials ratios, and most have sulfate resistant cement. The inset shows two of the beams tipped on their side to expose decreasing levels of deterioration with depth and moisture level. (66900, 58499)**



## Seawater Exposures

Concrete has been used in seawater exposures for decades with excellent performance. However, special care in mix design and material selection is necessary for these severe environments. A structure exposed to seawater or seawater spray is most vulnerable in the tidal or splash zone where there are repeated cycles of wetting and drying and/or freezing and thawing. Sulfates and chlorides in seawater require the use of low permeability concrete to minimize steel corrosion and sulfate attack (Fig. 1-34).

A cement resistant to moderate sulfate exposure is helpful. Portland cements with tricalcium aluminate ( $C_3A$ ) contents that range from 4% to 10% have been found to provide satisfactory protection against seawater sulfate attack, as well as protection against corrosion of reinforcement by chlorides. Proper concrete cover over reinforcing steel must be provided (see ACI 318). Water-cementitious material ratios should not exceed 0.40. In northern climates, the concrete must be properly air entrained with at least 6% air. High-strength concrete should be considered where large ice formations abrade the structure. See Stark (1995 and 2001), Farny (1996), and Kerkhoff (2001).



Fig. 1-34. Concrete bridges in seawater exposure must be specially designed for durability. (68667)

## Ettringite and Heat Induced Delayed Expansion

Ettringite, one form of calcium sulfoaluminate, is found in all portland cement paste. Calcium sulfate sources, such as gypsum, are added to portland cement during final grinding at the cement mill to prevent rapid setting and improve strength development. Sulfate is also present in supplementary cementitious materials and admixtures. Gypsum and other sulfate compounds react with calcium aluminate in cement to form ettringite within the first few hours after mixing with water. Most of the sulfate in cement is normally consumed to form ettringite or calcium monosul-



Fig. 1-35. White secondary ettringite deposits in void. Field width 64 $\mu$ m. (69547)

fate within 24 hours (Klemm and Miller 1997). At this stage ettringite is uniformly and discretely dispersed throughout the cement paste at a submicroscopic level (less than a micrometer in cross-section). This ettringite is often called primary ettringite.

If concrete is exposed to moisture for long periods of time (many years), the ettringite can slowly dissolve and reform in less confined locations. Upon microscopic examination, harmless white needle-like crystals of ettringite can be observed lining air voids. This reformed ettringite is usually called secondary ettringite (Fig. 1-35).

Concrete deterioration accelerates the rate at which ettringite leaves its original location in the paste to go into solution and recrystallize in larger spaces such as air voids or cracks. Both water and sufficient space must be present for the crystals to form. Cracks can form due to damage caused by frost action, alkali-aggregate reactivity, drying shrinkage, thermal effects, strain due to excessive stress, or other mechanisms.

Ettringite crystals in air voids and cracks are typically two to four micrometers in cross section and 20 to 30 micrometers long. Under conditions of extreme deterioration or decades in a moist environment, the white ettringite crystals can appear to completely fill voids or cracks. However, secondary ettringite, as large needle-like crystals, should not be interpreted as being harmful to the concrete (Detwiler and Powers-Couche 1997).

**Heat Induced Delayed Expansion.** Heat induced delayed expansion (HIDE)—also called delayed ettringite formation (DEF)—refers to a rare condition of internal sulfate attack\* in which mature concretes undergo expansion and

\*Internal sulfate attack refers to deterioration mechanisms occurring in connection with sulfate that is in the concrete at the time of placement.



cracking. Only concretes of particular chemical makeup are affected when they have achieved high temperatures, usually after the first few hours of placement (between 70°C and 100°C [158°F to 212°F] depending on the concrete ingredients and the time the temperature is achieved after casting). This can occur because the high temperature decomposes any initial ettringite formed and holds the sulfate and alumina tightly in the calcium silicate hydrate (C-S-H) gel of the cement paste. The normal formation of ettringite is thus impeded.

In the presence of moisture, sulfate desorbs from the confines of the C-S-H and reacts with calcium monosulfoaluminate to form ettringite in cooled and hardened concrete. After months or years of desorption, ettringite forms in confined locations within the paste. Such ettringite can exert crystallization pressures because it forms in a limited space under supersaturation. One theory: since concrete is rigid and if there are insufficient voids to accommodate the ettringite volume increase, expansion and cracks can occur. In addition, some of the initial (primary) ettringite may be converted to monosulfoaluminate at high temperatures and upon cooling revert back to ettringite. Because ettringite takes up more space than monosulfoaluminate from which it forms, the transformation is an expansive reaction. The mechanism causing expansion in the paste is not fully understood at this time; the true influence of ettringite formation on this expansion is still being investigated. Some research indicates that there is little relationship between ettringite formation and expansion.

As a result of an increase in paste volume, separation of the paste from the aggregates is usually observed with heat induced delayed expansion. It is characterized by the development of rims of ettringite around the aggregates (Fig. 1-36). At early stages of heat induced delayed expansion, the voids between paste and aggregate are empty (no ettringite present). It should be noted that concrete can sustain a small amount of this expansion without harm. Only extreme cases result in cracking, and often heat induced delayed expansion is associated with other deterioration mechanisms, especially alkali-silica reactivity.

Only concretes in massive elements that retain the heat of hydration or elements exposed to very high temperatures at an early age are at risk of HIDE; and of these only a few have the chemical makeup or temperature profile to cause detrimental expansion. Normal sized concrete elements cast and maintained near ambient temperatures cannot experience HIDE when sound materials are used.

Fly ash and slag may help control heat induced delayed expansion, along with control over early-age temperature development. For more information, see Lerch (1945), Day (1992), Klemm and Miller (1997), Thomas (1998), and Famy (1999).

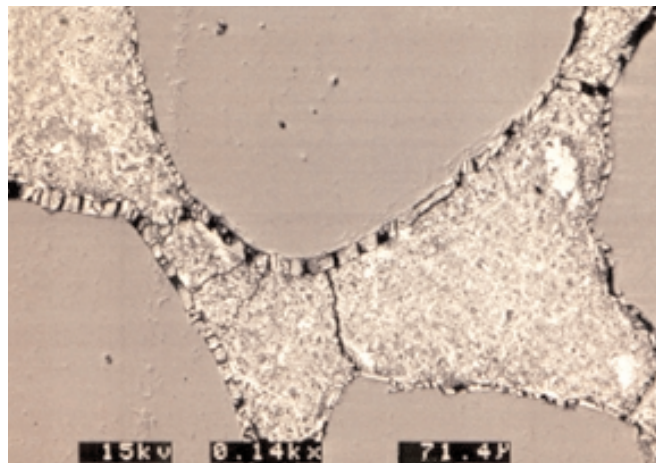


Fig. 1-36. Heat induced delayed expansion is characterized by expanding paste that becomes detached from non-expansive components, such as aggregates, creating gaps at the paste-aggregate interface. The gap can subsequently be filled with larger opportunistic ettringite crystals as shown here. Photo courtesy of Z. Zhang and J. Olek. (69154)

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