

Guide to Mass Concrete

Reported by ACI Committee 207

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Mass concrete is any volume of concrete with dimensions large enough to require that measures be taken to cope with the generation of heat from hydration of the cement and attendant volume change to minimize cracking. The design of mass concrete structures is generally based on durability, economy, and thermal action, with strength often being a secondary concern. This document contains a history of the development of mass concrete practice and discussion of materials and concrete mixture proportioning, properties, construction methods, and equipment. It covers traditionally placed and consolidated mass concrete and does not cover roller-compacted concrete.

Keywords: admixture; aggregate; air entrainment; batch; cement; compressive strength; cracking; creep; curing; durability; fly ash; formwork; grading; heat of hydration; mass concrete; mixing; mixture proportion; modulus of elasticity; placing; Poisson's ratio; pozzolan; shrinkage; strain; stress; temperature rise; thermal expansion; vibration; volume change.

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ACI 207.1R-05 supersedes ACI 207.1R-96 and became effective December 1, 2005.
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CHAPTER 1—INTRODUCTION AND HISTORICAL DEVELOPMENTS

1.1—Scope

Mass concrete is defined in ACI 116R as “any volume of concrete with dimensions large enough to require that measures be taken to cope with generation of heat from hydration of the cement and attendant volume change to minimize cracking.” The design of mass concrete structures is generally based on durability, economy, and thermal action, with strength often being a secondary, rather than a primary, concern. The one characteristic that distinguishes mass concrete from other concrete work is thermal behavior. Because the cement-water reaction is exothermic by nature, the temperature rise within a large concrete mass, where the heat is not quickly dissipated, can be quite high. Significant tensile stresses and strains may result from the restrained volume change associated with a decline in temperature as heat of hydration is dissipated. Measures should be taken where cracking due to thermal behavior may cause a loss of structural integrity and monolithic action, excessive seepage and shortening of the service life of the structure, or be aesthetically objectionable. Many of the principles in mass concrete practice can also be applied to general concrete work, whereby economic and other benefits may be realized.

This document contains a history of the development of mass concrete practice and a discussion of materials and concrete mixture proportioning, properties, construction methods, and equipment. This document covers traditionally placed and consolidated mass concrete, and does not cover roller-compacted concrete. Roller-compacted concrete is described in detail in ACI 207.5R.

Mass concreting practices were developed largely from concrete dam construction, where temperature-related cracking was first identified. Temperature-related cracking has also been experienced in other thick-section concrete structures, including mat foundations, pile caps, bridge piers, thick walls, and tunnel linings.

High compressive strengths are usually not required in mass concrete structures; however, thin arch dams are exceptions. Massive structures, such as gravity dams, resist loads primarily by their shape and mass, and only secondarily by their strength. Of more importance are durability and properties connected with temperature behavior and the tendency for cracking.

The effects of heat generation, restraint, and volume changes on the design and behavior of massive reinforced elements and structures are discussed in ACI 207.2R. Cooling and insulating systems for mass concrete are addressed in ACI 207.4R. Mixture proportioning for mass concrete is discussed in ACI 211.1.

1.2—History

When concrete was first used in dams, the dams were relatively small and the concrete was mixed by hand. The portland cement usually had to be aged to comply with a boiling soundness test, the aggregate was bank-run sand and

gravel, and proportioning was by the shovelful (Davis 1963). Tremendous progress has been made since the early 1900s, and the art and science of dam building practiced today has reached a highly advanced state. Presently, the selection and proportioning of concrete materials to produce suitable strength, durability, and impermeability of the finished product can now be predicted and controlled with accuracy.

Covered herein are the principal steps from those very small beginnings to the present. In large dam construction, there is now exact and automatic proportioning and mixing of materials. Concrete in 12 yd³ (9 m³) buckets can be placed by conventional methods at the rate of 10,000 yd³/day (7650 m³/day) at a temperature of less than 50 °F (10 °C) as placed, even during extremely hot weather. Grand Coulee Dam still holds the all-time record monthly placing rate of 536,250 yd³ (410,020 m³), followed by the more recent achievement at Itaipu Dam on the Brazil-Paraguay border of 440,550 yd³ (336,840 m³) (Itaipu Binacional 1981). The record monthly placing rate of 328,500 yd³ (250,200 m³) for roller-compacted concrete was achieved at Tarbela Dam in Pakistan. Lean mixtures are now made workable by means of air entrainment and other chemical admixtures and the use of finely divided pozzolanic materials. Water-reducing, strength-enhancing, and set-controlling chemical admixtures are effective in reducing the required cement content to a minimum and in controlling the time of setting. Placing rates for no-slump concrete, by using large earth-moving equipment for transportation and large vibrating rollers for consolidation, appear to be limited only by the size of the project and its plant's ability to produce concrete.

1.2.1 Before 1900—Before to the beginning of the twentieth century, much of the portland cement used in the United States was imported from Europe. All cements were very coarse by present standards, and quite commonly they were underburned and had a high free lime content. For dams of that period, bank-run sand and gravel were used without the benefit of washing to remove objectionable dirt and fines. Concrete mixtures varied widely in cement content and in sand-coarse aggregate ratio. Mixing was usually done by hand and proportioning by shovel, wheelbarrow, box, or cart. The effect of the water-cement ratio (w/c) was unknown, and generally no attempt was made to control the volume of mixing water. There was no measure of consistency except by visual observation of the newly mixed concrete.

Some of the dams were of cyclopean masonry in which “plums” (large stones) were partially embedded in a very wet concrete. The spaces between plums were then filled with concrete, also very wet. Some of the early dams were built without contraction joints and without regular lifts. There were, however, notable exceptions where concrete was cast in blocks; the height of lift was regulated, and concrete of very dry consistency was placed in thin layers and consolidated by rigorous hand tamping.

Generally, mixed concrete was transported to the forms by wheelbarrow. Where plums were employed in cyclopean masonry, stiff-leg derricks operating inside the work area moved the wet concrete and plums. The rate of placement

was, at most, a few hundred cubic yards (cubic meters) a day. Generally, there was no attempt to moist cure.

An exception to these general practices was the Lower Crystal Springs Dam, completed in 1890. This dam is located near San Mateo, California, about 20 miles (30 km) south of San Francisco. According to available information, it was the first dam in the United States in which the maximum permissible quantity of mixing water was specified. The concrete for this 154 ft (47 m) high structure was cast in a system of interlocking blocks of specified shape and dimensions. An old photograph indicates that hand tampers were employed to consolidate the dry concrete (concrete with a low water content and presumably very low workability). Fresh concrete was covered with planks as a protection from the sun, and the concrete was kept wet until hardening occurred.

1.2.2 1900 to 1930—After the turn of the century, construction of all types of concrete dams was greatly accelerated. More and higher dams for irrigation, power, and water supply were built. Concrete placement by means of towers and chutes became common. In the United States, the portland cement industry became well established, and cement was rarely imported from Europe. ASTM specifications for portland cement underwent little change during the first 30 years of the century, aside from a modest increase in fineness requirement determined by sieve analysis. Except for the limits on magnesia and loss on ignition, there were no chemical requirements. Character and grading of aggregates were given more attention during this period. Very substantial progress was made in the development of methods of proportioning concrete. The water-cement strength relationship was established by Abrams and his associates from investigations before 1918, when Portland Cement Association (PCA) Bulletin 1 appeared (Abrams 1918). Nevertheless, little attention was paid to the quantity of mixing water. Placing methods using towers and flat-sloped chutes dominated, resulting in the use of excessively wet mixtures for at least 12 years after the importance of the w/c had been established.

Generally, portland cements were employed without admixtures. There were exceptions, such as the sand-cements used by the U.S. Reclamation Service (now the U.S. Bureau of Reclamation [USBR]) in the construction of the Elephant Butte Dam in New Mexico and the Arrowrock Dam in Idaho. At the time of its completion in 1915, the Arrowrock Dam, a gravity-arch dam, was the highest dam in the world at 350 ft (107 m). The dam was constructed with lean interior concrete and a richer exterior face concrete. The mixture for interior concrete contained approximately 376 lb/yd³ (223 kg/m³) of a blended, pulverized granite-cement combination. The cement mixture was produced at the site by intergrinding approximately equal parts of portland cement and pulverized granite so that no less than 90% passed the No. 200 (75 μ m) mesh sieve. The interground combination was considerably finer than the cement being produced at that time.

Another exception occurred in the concrete for one of the abutments of Big Dalton Dam, a multiple-arch dam built by the Los Angeles County Flood Control District during the

late 1920s. Pumicite (a pozzolan) from Friant, California, was used as a 20% replacement by mass for portland cement.

During this period, cyclopean concrete went out of style. For dams of thick section, the maximum size of aggregate for mass concrete was increased to as large as 10 in. (250 mm). The slump test had come into use as a means of measuring consistency. The testing of 6 x 12 in. (150 x 300 mm) and 8 x 16 in. (200 x 400 mm) job cylinders became common practice in the United States. European countries generally adopted the 8 x 8 in. (200 x 200 mm) cube for testing the strength at various ages. Mixers of 3 yd³ (2.3 m³) capacity were commonly used near the end of this period, and there were some of 4 yd³ (3 m³) capacity. Only Type I cement (normal portland cement) was available during this period. In areas where freezing-and-thawing conditions were severe, it was common practice to use a concrete mixture containing 564 lb/yd³ (335 kg/m³) of cement for the entire concrete mass. The construction practice of using an interior mixture containing 376 lb/yd³ (223 kg/m³) and an exterior face mixture containing 564 lb/yd³ (335 kg/m³) was developed during this period to make the dam's face resistant to the severe climate and yet minimize the overall use of cement. In areas of mild climate, one class of concrete that contained amounts of cement as low as 376 lb/yd³ (223 kg/m³) was used in some dams.

An exception was the Theodore Roosevelt Dam built during the years of 1905 to 1911 in Arizona. This dam consists of a rubble masonry structure faced with rough stone blocks laid in portland cement mortar made with a cement manufactured in a plant near the dam site. For this structure, the average cement content has been calculated to be approximately 282 lb/yd³ (167 kg/m³). For the interior of the mass, rough quarried stones were embedded in a 1:2.5 mortar containing approximately 846 lb/yd³ (502 kg/m³) of cement. In each layer, the voids between the closely spaced stones were filled with a concrete containing 564 lb/yd³ (335 kg/m³) of cement, into which rock fragments were manually placed. These conditions account for the very low average cement content. Construction was slow, and Roosevelt Dam represents perhaps the last of the large dams built in the United States by this method of construction.

1.2.3 1930 to 1970—This was an era of rapid development in mass concrete construction for dams. The use of the tower and chute method declined during this period and was used only on small projects. Concrete was typically placed using large buckets with cranes, cableways, railroad systems, or a combination of these. On the larger and more closely controlled construction projects, the aggregates were carefully processed, ingredients were proportioned by weight, and the mixing water was measured by volume. Improvement in workability was brought about by the introduction of finely divided mineral admixtures (pozzolans), air entrainment, and chemical admixtures. Slumps as low as 3 in. (76 mm) were employed without vibration, although most projects in later years of this era used large spud vibrators for consolidation.

A study of the records and actual inspection of a considerable number of dams shows that there were differences in construction that could not be explained. Of two structures that appeared to

be of similar quality subjected to the same environment, one might exhibit excessive cracking while the other, after a similar period of service, would be in near-perfect condition. The meager records available on a few dams indicated wide internal temperature variations due to cement hydration. The degree of cracking was associated with the temperature rise.

ACI Committee 207, Mass Concrete, was organized in 1930 (originally as Committee 108) for the purpose of gathering information about the significant properties of mass concrete in dams and factors that influence these properties. Bogue (1949) and his associates, under the PCA fellowship at the National Bureau of Standards, had already identified the principal compounds in portland cement. Later, Hubert Woods and his associates engaged in investigations to determine the contributions of each of these compounds to heat of hydration and to the strength of mortars and concretes.

By the beginning of 1930, the Hoover Dam in Nevada was in the early stages of planning. Because of the unprecedented size of the Hoover Dam, investigations much more elaborate than any previously undertaken were carried out to determine the effects of factors, such as composition and fineness of cement, cement factor, temperature of curing, and maximum size of aggregate, on the heat of hydration of cement, compressive strength, and other properties of mortars and concrete.

The results of these investigations led to the use of low-heat cement in the Hoover Dam. The investigations also furnished information for the design of the embedded pipe cooling system used for the first time in the Hoover Dam. Low-heat cement was first used in the Morris Dam, near Pasadena, Calif., which was started a year before the Hoover Dam. For the Hoover Dam, the construction plant was of unprecedented capacity. Batching and mixing were completely automatic. The record day's output for the two concrete plants, equipped with 4 yd³ (3 m³) mixers, was over 10,000 yd³ (7600 m³). Concrete was transported in 8 yd³ (6 m³) buckets by cableways, and compacted initially by ramming and tamping. In the spring of 1933, large internal vibrators were introduced and were used thereafter for compacting the remainder of the concrete. Within approximately 2 years, 3,200,000 yd³ (2,440,000 m³) of concrete were placed.

Hoover Dam marked the beginning of an era of improved practices in large concrete dam construction. Completed in 1935 at a rate of construction then unprecedented, the practices employed there, with some refinements, have been in use on most of the large concrete dams that have been constructed in the United States and in many other countries since that time.

The use of a pozzolanic material (pumicite) was given a trial in the Big Dalton Dam by the Los Angeles County Flood Control District. For the Bonneville Dam, completed by the Corps of Engineers in 1938 in Oregon, a portland cement-pozzolan combination was used. It was produced by intergrinding the cement clinker with a pozzolan processed by calcining an altered volcanic material at a temperature of approximately 1500 °F (820 °C). The proportion of clinker to pozzolan was 3:1 by weight. This type of cement was selected for use at Bonneville on the basis of test results on concrete that indicated large extensibility and low temperature

rise. This is the earliest known concrete dam in the United States in which an interground portland-pozzolan cement has been used. The use of pozzolan as a separate cementing material to be added at the mixer, at a rate of 30% or more of total cementitious materials, has come to be regular practice by the USBR, the Tennessee Valley Authority (TVA), the United States Army Corps of Engineers (USACE), and others.

The chemical admixtures that function to reduce water in concrete mixtures, control setting, and enhance strength of concrete began to be seriously recognized in the 1950s as materials that could benefit mass concrete. In 1960, Wallace and Ore published their report on the benefit of these materials to lean mass concrete. Since this time, chemical admixtures have been used in most mass concrete.

Around 1945, it became standard practice to use intentionally entrained air for concrete in most structures that are exposed to severe weathering conditions. This practice was applied to the concrete of exposed surfaces of dams as well as to concrete pavements and reinforced concrete in general. Air-entraining admixtures introduced at the mixer have been used for both interior and exterior concretes of practically all dams constructed since 1945.

Placement of conventional mass concrete has remained largely unchanged since that time. The major new development in the field of mass concrete is the use of roller-compacted concrete.

1.2.4 1970 to present—During this era, roller-compacted concrete was developed and became the predominant method for placing mass concrete. Because roller-compacted concrete is now so commonly used, a separate report, ACI 207.5R, is the principal reference for this subject. Traditional mass concrete methods continue to be used for many projects, large and small, particularly where roller-compacted concrete would be impractical or difficult to use. This often includes arch dams, large walls, and some foundation works, particularly where reinforcement is required.

The continuing development of chemical admixtures has allowed the placement of very large underwater placements where the concrete flows laterally up to 100 ft. Float-in construction methods where structural elements are precast or prefabricated and later filled with underwater concrete have been developed. Construction of dam sections and powerhouses has been done in this manner.

1.2.5 Cement content—During the late 1920s and early 1930s, it was practically an unwritten law that no mass concrete for large dams should contain less than 376 lb/yd³ (223 kg/m³) of cement. Some authorities of that period believed that the cement factor should never be less than 564 lb/yd³ (335 kg/m³). The cement factor for the interior concrete of Norris Dam (Tennessee Valley Authority 1939) constructed by the Tennessee Valley Authority (TVA) in 1936, was 376 lb/yd³ (223 kg/m³). The degree of cracking was excessive. The compressive strength of the wet-screened 6 x 12 in. (150 x 300 mm) job cylinders at 1 year of age was 7000 psi (48.3 MPa). Similarly, core specimens 18 x 36 in. (460 x 910 mm) drilled from the first stage concrete containing 376 lb/yd³ (223 kg/m³) of cement at Grand Coulee Dam tested in excess of 8000 psi (55 MPa).

at the age of 2 years. Judged by composition, the cement was of the moderate-heat type corresponding to the present Type II. Considering the moderately low stresses within the two structures, it was evident that such high compressive strengths were quite unnecessary. A reduction in cement content on similar future constructions might be expected to substantially reduce the tendency toward cracking.

For Hiwassee Dam, completed by TVA in 1940, the 376 lb/yd³ (223 kg/m³) cement-content barrier was broken. For that structure, the cement content of the mass concrete was only 282 lb/yd³ (167 kg/m³), an unusually low value for that time. Hiwassee Dam was singularly free from thermal cracks, which began a trend toward reducing the cement content, which is still continuing. Since that time, the Type II cement content of the interior mass concrete has been approximately 235 lb/yd³ (140 kg/m³) and even as low as 212 lb/yd³ (126 kg/m³). An example of a large gravity dam for which the Type II cement content for mass concrete was 235 lb/yd³ (140 kg/m³) is Pine Flat Dam in California, completed by the USACE in 1954. In arch-type high dams where stresses are moderately high, the cement content of the mass mixture is usually in the range of 300 to 450 lb/yd³ (180 to 270 kg/m³), with the higher cement content being used in the thinner and more highly stressed dams of this type.

Examples of cementitious contents, including pozzolan, for more recent dams are:

- *Arch dams*—282 lb/yd³ (167 kg/m³) of cement and pozzolan in Glen Canyon Dam, a relatively thick arch dam in Arizona, completed in 1963; 373 lb/yd³ (221 kg/m³) of cement in Morrow Point Dam in Colorado, completed in 1968; and 303 to 253 lb/yd³ (180 to 150 kg/m³) of portland-pozzolan Type IP cement in El Cajon Dam on the Humuya River in Honduras, completed in 1984.
- *Straight gravity dams*—226 lb/yd³ (134 kg/m³) of Type II cement in Detroit Dam in Oregon, completed in 1952; 194 lb/yd³ (115 kg/m³) of Type II cement and fly ash in Libby Dam in Montana, completed in 1972; and 184 lb/yd³ (109 kg/m³) of Type II cement and calcined clay in Ilha Solteira Dam in Brazil, completed in 1973.

1.3—Temperature control

The practice of precooling concrete materials before mixing to achieve a lower maximum temperature of interior mass concrete during the hydration period began in the early 1940s, and has been extensively used in the construction of large dams.

The first practice of precooling appears to have occurred during the construction of Norfork Dam from 1941 to 1945 by the USACE. The plan was to introduce crushed ice into the mixing water during the warmer months. By so doing, the temperature of freshly mixed mass concrete could be reduced by approximately 10 °F (5.6 °C). Not only has crushed ice been used in the mixing water, but coarse aggregates have been precooled either by cold air or cold water before batching. Recently, both fine and coarse aggregates in a moist condition have been precooled by various means, including vacuum saturation and liquid nitrogen injection. It has become almost standard practice in the United States to use precooling for large dams in regions where the summer

temperatures are high to ensure that the temperature of concrete, as it is placed, does not exceed approximately 50 °F (10 °C).

On some large dams, including Hoover (Boulder) Dam, a combination of precooling and postcooling refrigeration by embedded pipe has been used (USBR 1949). A good example of this practice is Glen Canyon Dam, where the ambient temperatures can be greater than 100 °F (38 °C) during the summer months. The temperature of the precooled fresh concrete did not exceed 50 °F (10 °C). Both refrigerated aggregate and crushed ice were used to achieve this low temperature. By means of embedded-pipe refrigeration, the maximum temperature of hardening concrete was kept below 75 °F (24 °C). Postcooling is sometimes required in gravity and in arch dams that contain transverse joints so that transverse joints can be opened for grouting by cooling the concrete after it has hardened. Postcooling to control cracking is also done for control of peak temperatures.

1.4—Long-term strength design

A most significant development of the 1950s was the abandonment of the 28-day strength as a design requirement for dams. Maximum stresses under load do not usually develop until the concrete is at least 1 year old. Under mass curing conditions, with the cement and pozzolans customarily employed, the gain in concrete strength between 28 days and 1 year is generally large. ACI 232.2R reports that the gain can range from 30 to more than 100%, depending on the quantities and proportioning of cementitious materials and properties of the aggregates. It has become the practice of some designers of dams to specify the desired strength of mass concrete at later ages, such as at 1 or 2 years. For routine quality control in the field, 6 x 12 in. (150 x 300 mm) cylinders are normally used with aggregate larger than 1-1/2 in. (37.5 mm). The aggregate larger than 1-1/2 in. (37.5 mm) is removed from the concrete by wet-screening. Strength requirements of the wet-screened concrete are correlated with the specified full-mixture strength by laboratory tests.

CHAPTER 2—MATERIALS AND MIXTURE PROPORTIONING

2.1—General

As is the case with other concrete, mass concrete is composed of cement, aggregates, and water, and frequently pozzolans and admixtures. The objective of mass concrete mixture proportioning is the selection of combinations of materials that will produce concrete to meet the requirements of the structure with respect to economy; workability; dimensional stability and freedom from cracking; low temperature rise; adequate strength; durability; and, in the case of hydraulic structures, low permeability. This chapter describes materials that have been successfully used in mass concrete construction and the factors influencing their selection and proportioning. The recommendations contained herein may need to be adjusted for special uses, such as for massive precast beam segments, tremie placements, and roller-compacted concrete. Guidance in proportioning mass concrete can also be found in ACI 211.1, particularly

Appendix 5, which details procedures for mass concrete proportioning.

2.2—Cements

ACI 207.2R and 207.4R contain additional information on cement types and effects on heat generation. The following types of hydraulic cement are suitable for use in mass concrete construction:

- *Portland cement*—Types I, II, IV, and V, as covered by ASTM C 150;
- *Blended cement*—Types P, IP, S, IS, I(PM), and I(SM), as covered by ASTM C 595; and
- *Hydraulic cement*—Types GU, MS, HS, MH, and LH, as covered by ASTM C 1157.

When portland cement is used with pozzolan or with other cements, the materials are batched separately at the mixing plant. Economy and low temperature rise are both achieved by limiting the total cement content to as small an amount as possible.

Type I and GU cements are suitable for use in general construction. They are not recommended for use alone in mass concrete without other measures that help to control temperature problems because of their substantially higher heat of hydration.

Type II (moderate heat) and MH cements are suitable for mass concrete construction because they have a moderate heat of hydration, which is important to the control of cracking. Type II must be specified with the moderate heat option as most Type II and MS cements are designed for moderate sulfate resistance and do not have moderate heat properties. Specifications for Type II portland cement require that it contain no more than 8% tricalcium aluminate (C_3A), the compound that contributes substantially to early heat development in concrete. Optional specifications for Type II cement place a limit of 58% or less on the sum of C_3A and C_3S or a limit on the heat of hydration to 70 cal/g (290 kJ/kg) at 7 days. When one of the optional requirements is specified, the 28-day strength requirement for cement paste under ASTM C 150 is reduced due to the slower rate of strength gain of this cement.

Types IV and LH, low-heat cements, may be used where it is desired to produce low heat development in massive structures. They have not been used in recent years because they have been difficult to obtain and, more importantly, because experience has shown that in most cases, heat development can be controlled satisfactorily by other means. Type IV specifications limit the C_3A to 7%, the C_3S to 35%, and place a minimum on the C_2S of 40%. At the option of the purchaser, the heat of hydration may be limited to 60 cal/g (250 kJ/kg) at 7 days and 70 cal/g (290 kJ/kg) at 28 days. Type IV cement is generally not available in the United States.

Type V and HS sulfate-resistant cements are available in areas with high-sulfate soils, and will often have moderate heat characteristics. They are usually available at a price higher than Type I. They are usually both low alkali (less than 0.6 equivalent alkalies) and low heat (less than 70 cal/g at 7 days).

Type IP portland-pozzolan cement is a uniform blend of portland cement or portland blast-furnace slag cement and fine pozzolan. Type P is similar, but early strength requirements are lower. They are produced either by intergrinding portland cement clinker and pozzolan or by blending portland cement or portland blast-furnace slag cement and finely divided pozzolan. The pozzolan constituents are between 15 and 40% by weight of the portland-pozzolan cement, with Type P generally having the higher pozzolan content.

Type I(PM) pozzolan-modified portland cement contains less than 15% pozzolan, and its properties are close to those of Type I cement. A heat of hydration limit of 70 cal/g (290 kJ/kg) at 7 days is an optional requirement for Types IP and I(PM) by adding the suffix (MH). A limit of 60 cal/g (250 kJ/kg) at 7 days is optional for Type P by adding the suffix (LH).

Type IS portland blast-furnace slag cement is a uniform blend of portland cement and fine blast-furnace slag. It is produced either by intergrinding portland cement clinker and granulated blast-furnace slag or by blending portland cement and finely ground-granulated blast-furnace slag. The amount of slag used may vary between 25 and 70% by weight of the portland blast-furnace slag cement. This cement has sometimes been used with a pozzolan. Type S slag cement is a finely divided material consisting of a uniform blend of granulated blast-furnace slag and hydrated lime in which the slag constituent is at least 70% of the weight of the slag cement. Slag cement is generally used in a blend with portland cement for making concrete.

Type I(SM) slag-modified portland cement contains less than 25% slag, and its properties are close to those of Type I cement. Optional heat-of-hydration requirements can be applied to Types IS and I(SM), similar to those applied to Types IP, I(PM), and P.

Low-alkali cements are defined by ASTM C 150 as portland cements containing not more than 0.60% alkalies calculated as the percentage of Na_2O plus 0.658 times the percentage of K_2O . These cements can be specified when the cement is to be used in concrete with aggregate that may be deleteriously reactive. The use of low-alkali cement may not always control highly reactive noncrystalline siliceous aggregate. It may also be advisable to use a proven pozzolan to ensure control of the alkali-aggregate reaction.

2.3—Pozzolans and ground slag

A pozzolan is generally defined as a siliceous or siliceous-and-aluminous material that possesses little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties. Pozzolans are ordinarily governed and classified by ASTM C 618 as natural (Class N) or fly ash (Class F or C). There are some pozzolans, such as the Class C fly ash, that contain significant amounts of compounds like those of portland cement. The Class C fly ashes likewise have cementitious properties by themselves that may contribute significantly to the strength of concrete.

Pozzolans react chemically with the calcium hydroxide or hydrated lime liberated during the hydration of portland

cement to form a stable strength-producing cementitious compound. For best activity, the siliceous ingredient of a pozzolan should be in an amorphous state, such as glass or opal. Crystalline siliceous materials, such as quartz, do not combine readily with lime at a normal temperature unless they are ground into a very fine powder. The use of fly ash in concrete is discussed in ACI 232.2R, and the use of ground-granulated blast-furnace slag is discussed in ACI 233R.

Natural pozzolanic materials occur in large deposits throughout the western United States in the form of obsidian, pumicite, volcanic ashes, tuffs, clays, shales, and diatomaceous earth. These natural pozzolans usually require grinding. Some of the volcanic materials are of suitable fineness in their natural state. The clays and shales, in addition to grinding, should be activated to form an amorphous state by calcining at temperatures in the range of 1200 to 1800 °F (650 to 980 °C).

Fly ash is the flue dust from burning ground or powdered coal. Suitable fly ash can be an excellent pozzolan if it has a low carbon content, a fineness approximately the same as that of portland cement, and occurs in the form of very fine, glassy spheres. Because of its shape and texture, the water requirement is usually reduced when fly ash is used in concrete. There are indications that, in many cases, the pozzolanic activity of the fly ash can be increased by cracking the glass spheres by means of grinding. This may, however, reduce its lubricating qualities and increase the water requirement of the concrete. High-silica Class F fly ashes are generally excellent pozzolans; however, some Class C fly ashes may contain such a high CaO content that, while possessing good cementitious properties, they may be unsuitable for controlling alkali-aggregate reaction or for improving sulfate resistance of concrete. Additionally, the Class C fly ash is less helpful in lowering heat generation in the concrete.

Pozzolans in mass concrete may be used to reduce portland cement factors for better economy, lower internal heat generation, improve workability, and lessen the potential for damage from alkali-aggregate reactivity and sulfate attack. It should be recognized, however, that properties of different pozzolans may vary widely. Before a pozzolan is used, it should be tested in combination with the project cement and aggregates to establish that the pozzolan will beneficially contribute to the quality and economy of the concrete. Compared with portland cement, the strength development from pozzolanic action is slow at early ages, but continues at a higher level for a longer time. Early strength of a portland-cement-pozzolan concrete would be expected to be lower than that of a portland-cement concrete designed for equivalent strength at later ages. Where some portion of mass concrete is required to attain strength at an earlier age than is attainable with the regular mass concrete mixture, the increased internal heat generated by a substitute earlier-strength concrete may be accommodated by other means. Where a pozzolan is being used, it may be necessary to temporarily forego the use of the pozzolan and otherwise accommodate the increased internal heat generated by the use of straight portland cement. If there is a dangerous potential from

alkali-aggregate reaction, however, the pozzolan should be used, while expedited strength increase is achieved by additional cement content.

Pozzolans, particularly natural types, have been found effective in reducing the expansion of concrete containing reactive aggregates. The amount of this reduction varies with the chemical makeup, the fineness of the pozzolan, and the amount employed. For some pozzolans, the reduction in expansion may exceed 90%. Pozzolans reduce expansion by consuming alkalis from the cement before they can enter into deleterious reactions with the aggregates. Where alkali-reactive aggregates are used, it is considered good practice to use both a low-alkali cement and a pozzolan of proven corrective ability. Alkali-aggregate reactions are discussed in ACI 221R.

Results of some experiments reported by Mather (1974) indicate that for interior mass concrete, where stresses are moderately low, a much higher proportion of pozzolan-to-cement may be used when it is more economical and the desired strength is obtained at later ages. For example, the results of laboratory tests indicate that an air-entrained mass concrete, containing 94 lb/yd³ (53 kg/m³) of cement plus fly ash in an amount equivalent in volume to 188 lb (112 kg) of cement, has produced a very workable mixture for which the water content was less than 100 lb/yd³ (60 kg/m³). The 1-year compressive strength of wet-screened 6 x 12 in. (150 x 300 mm) cylinders of this concrete was approximately 3000 psi (21 MPa). For such a mixture, the mass temperature rise would be exceedingly small. For gravity dams of moderate height, where the material would be precooled so that the concrete, as it reaches the forms, will be approximately 15 °F (8 °C) below the mean annual or rock temperature, there is the possibility that neither longitudinal nor transverse contraction joints would be required. The maximum temperature of the interior of the mass due to cement hydration might not be appreciably greater than the mean annual temperature.

The particle shapes of concrete aggregates and their effect on workability have become less important because of the improved workability that is obtainable through the use of pozzolans and air-entraining and other chemical admixtures. The development of new types of pozzolans, such as rice hull ash and silica fume, may find a promising place in future mass concrete work.

Finely ground-granulated iron blast-furnace slag, commonly referred to as slag cement, may also be used as a separate ingredient with portland cement as a cementitious material in mass concrete. Requirements on finely ground slag for use in concrete are specified in ASTM C 989. If used with Type I portland cement, proportions of at least 70% finely ground slag of total cementitious material may be needed with an active slag to produce a cement-slag combination that will have a heat of hydration less than 60 cal/g (250 kJ/kg) at 7 days. The addition of slag will usually reduce the rate of heat generation due to a slightly slower rate of hydration. Finely ground slag also produces many of the beneficial properties in concrete that are achieved with suitable pozzolans, such as reduced permeability, control of expansion from reactive aggregate, sulfate resistance,

and improved workability. Finely ground slag, however, is usually used in much higher percentages than pozzolan to achieve similar properties.

2.4—Chemical admixtures

Chemical admixtures can provide important benefits to mass concrete in its plastic state by increasing workability, reducing water content, or both. Also, chemical admixtures can be used for retarding initial setting, modifying the rate or capacity for bleeding, reducing segregation, and reducing rate of slump loss. Chemical admixtures can provide important benefits to mass concrete in its hardened state by lowering heat evolution during hardening, increasing strength, lowering cement content, increasing durability, decreasing permeability, and improving abrasion or erosion resistance. A full coverage of admixtures is contained in ACI 212.3R. The chemical admixtures that are important to mass concrete are classified as air-entraining, water-reducing, or set-controlling.

Air-entraining admixtures are materials that produce minute air bubbles in concrete during mixing with resultant improved workability, reduced segregation, lessened bleeding, lowered permeability, and increased resistance to damage from freezing-and-thawing cycles. The entrainment of air greatly improves the workability of lean concrete and permits the use of harsher and more poorly graded aggregates and those of undesirable shapes. Air entrainment also facilitates the placing and handling of mass concrete. Each 1% of entrained air permits a reduction in mixing water from 2 to 4%, with some improvement in workability and no loss in slump. Durability, as measured by the resistance of concrete to deterioration from freezing-and-thawing, is greatly improved if the spacing of the air bubble system is such that no point in the cement matrix is more than 0.008 in. (0.20 mm) from an air bubble.

Entrained air will generally reduce the strength of most concrete. Where the cement content is held constant and advantage is taken of the reduced water requirement, air entrainment in lean mass concrete has a negligible effect on strength, and may even slightly increase it. Among the factors that influence the amount of entrained air in concrete for a given amount of agent are: grading and particle shape of the aggregate, richness of the mixture, presence of other admixtures, mixing time, slump, and temperature of the concrete. For a given quantity of air-entraining admixture, air content increases with increases in slump up to 6 in. (150 mm), and decreases with increases in amount of fines, temperature of concrete, and mixing time. If fly ash is used that contains carbon, an increased dosage of air-entraining admixture is required. Most specifications for mass concrete require that the quantity of entrained air, as determined from concrete samples wet-sieved through the 1-1/2 in. (37.5 mm) sieve, be approximately 5%, although in some cases as high as 8%. Requirements for air-entraining admixtures are contained in ASTM C 260.

Water-reducing and set-controlling admixtures generally consist of one or more of the following: lignosulfonic acid,

hydroxylated carboxylic acid, polymeric carbohydrates, and naphthalene or melamine types of high-range water reducers.

Accelerating admixtures are not used in mass concrete because high early strength is not necessary in such work and because accelerators contribute to undesirable heat development in the concrete mass.

Water-reducing admixtures are used to reduce the mixing water to increase strength and reduce shrinkage of the concrete, increase the workability of the concrete, or produce the same strength with less cement. Set-controlling admixtures can be used to keep the concrete plastic longer in massive blocks so that successive layers can be placed and vibrated before the underlayer sets. Admixtures from the aforementioned first three families of materials generally will reduce the water requirement up to approximately 10%, retard initial set at least 1 hour (but not reduce slump loss), and appreciably increase the strength. When a retarder is used, the strength after 12 hours is generally comparable to that of concrete containing no admixture. Depending on the richness of the concrete, composition of the cement, temperature, and other factors, the use of chemical admixtures will usually result in significant increases in 1-, 7-, 28-day, and later strengths. This gain in strength cannot be explained by the amount of the water reduction or by the degree of change in w/c ; the chemicals have a favorable effect on the hydration of the cement. Admixtures of the carboxylic acid family augment bleeding. High-range water-reducing admixtures have not been used in mass concrete construction, although these admixtures were used in some mass concrete in Guri Dam in Venezuela and have been used in reinforced mass concrete foundations. Continued admixture development has resulted in very stable admixtures that maintain consistent and long-term performance. This has resulted in a wide range of water-reducing admixtures to be used in most mass concrete mixtures today. Requirements for chemical admixtures are contained in ASTM C 494.

2.5—Aggregates

Coarse and fine aggregate and terms relating to aggregates are defined in ASTM C 125. Additional information on aggregates is contained in ACI 221R.

Fine aggregate is that fraction almost entirely passing the No. 4 (4.75 mm) sieve. It may be composed of natural grains, manufactured grains obtained by crushing larger-size rock particles, or a mixture of the two. Fine aggregate should consist of hard, dense, durable, uncoated particles. Fine aggregate should not contain harmful amounts of clay, silt, dust, mica, organic matter, or other impurities to such an extent that, either separately or together, they render it impossible to attain the required properties of concrete when using normal proportions of the ingredients. Deleterious substances are usually limited to the percentages by weight given in Table 2.1. For exposed concrete in the zone of fluctuating water level for bridge piers, dams, and other hydraulic structures, the maximum allowable percentage of the deleterious substance should be 50% lower than that given in Table 2.1 for face concrete in the zone of fluctuating water levels. It can be 50% higher for concrete consistently immersed in water and for concrete in the interior of massive dams.

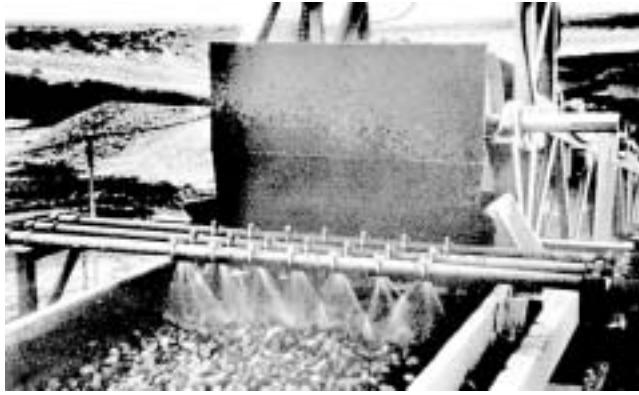


Fig. 2.1—Coarse aggregate rewashing.

The grading of fine aggregate strongly influences the workability of concrete. A good grading of sand for mass concrete should be within the limits shown in Table 2.2. Laboratory investigation, however, may show other gradings to be satisfactory. This permits a rather wide latitude in gradings for fine aggregate.

Although the grading requirements themselves may be rather flexible, it is important that once the proportion is established, the grading of the sand be maintained reasonably constant to avoid variations in the workability of the concrete.

Coarse aggregate is defined as gravel, crushed gravel, crushed rock, or a mixture of these, nominally larger than the No. 4 (4.75 mm) and smaller than the 6 in. (150 mm) sizes for large structures. Massive structural concrete structures, such as powerhouses or other heavily reinforced units that are considered to be in the mass concrete category, have successfully used smaller-sized coarse aggregates, usually of 3 in. (75 mm) maximum size, but with some as small as 1-1/2 in. (37.5 mm). The use of smaller aggregate may be dictated by the close spacing of reinforcement or embedded items, or by the unavailability of larger aggregates. This results in higher cement contents with attendant adverse effects on internal heat generation and cracking potential that should be offset by greater effort to reduce the cement requirement and concrete placing temperatures. The maximum size of coarse aggregate should not exceed 1/4 of the least dimension of the structure nor 2/3 of the least clear distance between reinforcing bars in horizontal mats or where there is more than one vertical reinforcing curtain next to a form. Otherwise, the rule for mass concrete should be to use the largest practical size of coarse aggregate.

Coarse aggregate should consist of hard, dense, durable, uncoated particles. Rock that is friable or tends to degrade during processing, transporting, or in storage should be avoided. Rock having an absorption greater than 3% or a specific gravity less than 2.5 is not generally considered suitable for exposed mass concrete subjected to freezing and thawing. Sulfates and sulfides, determined by chemical analysis and calculated as SO_3 , should not exceed 0.5% of the weight of the coarse aggregate. The percentage of other deleterious substances such as clay, silt, and fine dust in the coarse aggregate as delivered to the mixer should generally not exceed the values outlined in Table 2.3.

Table 2.1—Maximum allowable percentages of deleterious substances in fine aggregate (by weight)

Clay lumps and friable particles	3.0
Material finer than No. 200 (75 μm) sieve:	
For concrete subject to abrasion	3.0*
For all other concrete	5.0*
Coal and lignite:	
Where surface appearance of concrete is important	0.5
All other concrete	1.0

*In the case of manufactured sand, if material passing No. 200 (75 μm) sieve consists of dust of fracture, essentially free of clay or shale, these limits may be increased to 5% for concrete subject to abrasion and 7% for all other concrete.

Table 2.2—Fine aggregate for mass concrete*

Sieve designation	Percentage retained, individual by weight
3/8 in. (9.50 mm)	0
No. 4 (4.75 mm)	0 to 5
No. 8 (2.36 mm)	5 to 15
No. 16 (1.18 mm)	10 to 25
No. 30 (600 μm)	10 to 30
No. 50 (300 μm)	15 to 35
No. 100 (150 μm)	12 to 20
Pan fraction	3 to 7

*U.S. Bureau of Reclamation (1981).

Table 2.3—Maximum allowable percentages of deleterious substance in coarse aggregate (by weight)

Material passing No. 200 sieve (75 μm)	0.5
Lightweight material	2.0
Clay lumps	0.5
Other deleterious materials	1.0

Figure 2.1 shows a coarse-aggregate rewashing screen at the batch plant where dust and coatings accumulating from stockpiling and handling can be removed to ensure aggregate cleanliness.

Theoretically, the larger the maximum aggregate size, the less cement is required in a given volume of concrete to achieve the desired quality. This theory is based on the fact that with well-graded materials, the void space between the particles (and the specific surface) decreases as the range in sizes increases. It has been demonstrated (Fig. 2.2), however, that to achieve the greatest cement efficiency, there is an optimum maximum size for each compressive strength level to be obtained with a given aggregate and cement (Higginson et al. 1963). While the maximum size of coarse aggregate is limited by the configuration of the forms and reinforcing steel, in most unreinforced mass concrete structures, these requirements permit an almost unlimited maximum aggregate size. In addition to availability, the economical maximum size is determined by the design strength and problems in processing, batching, mixing, transporting, placing, and consolidating the concrete. Large aggregate particles of irregular shape tend to promote cracking around the larger particles because of differential