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Mass Concrete—Guide

Reported by ACI Committee 207

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Mass Concrete—Guide

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Mass Concrete—Guide

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This guide 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 for massive structures such as dams and provides information applicable to mass structural heavily reinforced concrete and for thermally controlled concrete such as bridge elements and building foundations. This guide does not cover roller-compacted concrete.

Keywords: cement; cracking; fly ash; heat of hydration; mass concrete; mixture proportioning; supplementary cementitious materials; temperature rise; thermal control plan; thermal expansion; volume change.

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CHAPTER 1—INTRODUCTION AND HISTORICAL DEVELOPMENTS

1.1—Scope

Mass concrete covered by this guide generally falls into two classifications, or types. The first type is the traditional mass concrete of structures such as dams, where most of the structure is mass concrete and is constructed of intertwined placements. The second type consists of individual or distinct placements such as high-rise building foundations or bridges, and is increasingly referred to as thermally controlled concrete. Both types of mass concrete have similar principles and basic considerations; however, thermally controlled concrete is often constructed with commercial ready mixed concrete. Thus, it may be designed to be pumpable and can consist of self-consolidating, high-strength, or high-performance concrete, which typically results in concrete containing much higher cementitious materials content than traditional mass concrete. Although this guide mainly focuses on guidance for traditional mass concrete, much of the information can also be applicable to thermally controlled concrete.

The design of traditional mass concrete structures, such as dams, is generally based on durability, economy, and thermal requirements. Strength performance is often a secondary requirement, rather than a primary concern, and is sometimes specified to be achieved at an age of 56 or 90 days instead of 28 days.

The one characteristic that distinguishes mass concrete from other concrete work is thermal behavior. Because the reaction between water and cement 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 a decline in temperature as heat from hydration is dissipated at the volume extremities but not at the mass core. Measures should be taken where cracking due to thermal behavior may adversely affect structural integrity, durability, or aesthetics.

This guide contains a history of the development of mass concrete practice and a discussion of materials and concrete mixture proportioning, properties, construction methods, and equipment.

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 concrete structures, including mat foundations, pile caps, bridge piers, superstructure elements, roadway patches, and tunnel linings.

High compressive strengths are not typically required in traditional mass concrete structures; however, there are some cases, such as thin arch dams, where high-strength concrete may be specified. Massive structures, such as gravity dams, resist loads primarily by their shape and mass; strength is of secondary importance. 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](#).

1.2—History

Historically, mass concrete considerations evolved out of the use of concrete in dams. The first concrete 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 record monthly placing rate of 536,250 yd³ (410,020 m³), followed by the Itaipu Dam on the Brazil-Paraguay border with 440,550 yd³ (336,840 m³) ([Itaipu Binacional 1981](#)).

1.2.1 Before 1900—Before 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 fine-to-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. 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 the concrete.

An exception to these general practices was the Lower Crystal Springs Dam, completed in 1890. This dam is located near San Mateo, CA, approximately 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 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 (1918)** from investigations before 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 exces-

sively 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 mm) 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, CA, was used as a 20% replacement by mass for portland cement.

In the early part of the twentieth century, cyclopean concrete went out of style. For dams of thick section, the maximum size of aggregate for mass concrete increased to 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. By the end of the 1920s, mixers of 3 yd³ (2.3 m³) capacity were commonly used, and there were some of 4 yd³ (3 m³) capacity. Only Type I cement (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 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 (**TVA 1940**).

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 void between the closely spaced stones were filled with concrete containing 564 lb/yd³ (335 kg/m³) of cement.

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 mass, and the mixing water was measured by volume. Improvement in workability was brought about by the introduction of supplementary cementitious materials (SCMs), 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 conditions 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 records available on a few dams indicated wide internal temperature variations due to cement hydration. To better understand the discrepancies borne from thermal behavior observed in the field, the American Concrete Institute (ACI) established a committee to study the effects of mass concrete.

ACI Committee 207, Mass Concrete, was organized in 1930 for the purpose of gathering information about the significant properties of mass concrete in dams and factors that influence these properties. Bogue (1929) had already identified the principal compounds in portland cement. 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 (Woods et al. 1932).

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, in-depth investigations 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 (U.S. Bureau of Reclamation 2009).

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, CA, 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 mass. This type of cement was selected for use at Bonneville based on test results on concrete that indicated low temperature rise. This is the earliest known concrete dam in the United States in which an interground portland-pozzolan cement was used. The use of pozzolan as a separate cementitious 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 and 1960s (Wallace and Ore 1960) as materials that could benefit mass concrete. Since that time, chemical admixtures have been used in most mass concrete.

Around 1945, it became standard practice to intentionally entrain air for concrete in most structures exposed to severe weathering conditions. This practice applied to the concrete of exposed surfaces of dams as well as to concrete pavements and reinforced concrete in general. Air-entraining admixtures have been used for both interior and exterior concretes of practically all dams constructed since 1945. Air entrainment is sometimes specified in mass concrete in areas that are not affected by freezing and thawing as a method to increase workability without the addition of cement; this was used most recently on the Folsom Dam Auxiliary Control Structure in Folsom, CA (U.S. Bureau of Reclamation 1999).

1.2.4 1970 to present—During this era, roller-compacted concrete was developed and became the predominant method for placing mass concrete of dams. Because roller-compacted concrete is now commonly used, ACI 207.5R is a principal reference for this subject. Other concrete placement methods continue to be used on 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 foundations, particularly where reinforcement is required.

The continuing development of chemical admixtures has allowed very large underwater placements where the concrete flows laterally up to 100 ft (30 m). 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 have been completed in this manner.

Concern over the effects of high internal temperatures, temperature differences within elements, and placements that were traditionally not considered mass concrete began in the mid-1990s. These concerns started with a noted increase in the cracking of structures and the increased focus on long service life of transportation infrastructure. The increase in cracking was correlated with the use of concrete with high cement and SCM contents, finer cement grinding, high early compressive strength, and rapid construction practices. These practices resulted in concrete placements having high temperature gains and internal temperature differentials. Around the same time, delayed ettringite formation (DEF) came into notoriety in the precast industry and was also identified as a potential deterioration mechanism in non-precast concrete. This led to an increased focus on thermal control of concrete placements for commercial and transportation projects, with these placements being referred to as mass concrete. There is currently no standard definition of specific characteristics of concrete or placements that require control of temperatures and temperature differences, although efforts are underway to develop such a definition based on the dimensions of the concrete placement and heat generation of the concrete used in the placement.

ACI 301, ACI 350, and ACI 349 have specification requirements for placements designated to be treated as mass concrete. ACI 301 recommends that placements that are 4 ft (1.2 m) thick or greater, or capable of generating a large amount of heat at early ages should be treated as mass concrete. Placements that trap heat such as those where heat in soil does not allow placement to cool or in stacked placements with too little time provided for adequate heat dissipation should also be considered mass concrete. For such placements, ACI 301 specifies a maximum temperature limit of 160°F (70°C) and temperature differences not exceeding 35°F (20°C). Control of temperatures and temperature variations within the placement is required from the time the concrete is placed until the hottest portion of the concrete cools to the temperature, which is specified to be acceptable based on the average air temperature. This requirement is intended to maintain the maximum temperature and temperature variation within the specified limits, which often occurs if thermal controls are discontinued too early. ACI 301 also requires development and submittal of a thermal control plan to describe specific measures that will be used to control temperatures and temperature differences, and temperature monitoring to demonstrate that temperature requirements have not been exceeded. All the cited require-

ments of ACI 301 are the default requirements, which can be modified by the specifier or by request of the contractor, subject to review and approval by the engineer.

1.2.5 Cement content—During the late 1920s and early 1930s, it was practically an unwritten law that mass concrete for large dams should contain more than 376 lb/yd³ (223 kg/m³) of cement. However, 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 (TVA 1940), 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, 18 x 36 in. (460 x 910 mm) core specimens 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 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 unnecessary.

For Hiwassee Dam, completed by TVA in 1940, the cement content of the mass concrete was 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. 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 typically higher than large gravity dams, 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:

a) *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.

b) *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.

c) *Spillways*—128 lb/yd³ (76 kg/m³) of cement and 383 lb/yd³ (227 kg/m³) of slag cement for 3000 psi (21 MPa) concrete, and 425 lb/yd³ (252 kg/m³) of cement and 180 lb/yd³ (107 kg/m³) of slag cement for 1000 psi (7 MPa) concrete.

concrete in Folsom Dam Auxiliary Spillway in California, completed in 2017.

Structural mass concrete mixtures will often be proportioned with higher total cementitious materials content than typical concrete mixtures used for dam construction. These proportions are often needed to meet requirements for high strength, placement in highly congested areas, pumpability, and other constraints in structural elements. For example, structural mass concrete mixtures often have a total cementitious materials content in excess of 700 lb/yd³ (415 kg/m³). High replacement percentages of SCMs are often used to mitigate high temperature rise in structural mass concrete mixtures. For example, replacement of cement with 40 to 50% fly ash or 70% slag cement is common.

1.2.6 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 Norfolk 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 also been precooled either by cold air or cold water before batching. Both fine and coarse aggregates have been precooled by various means, including vacuum saturation and liquid nitrogen injection during the batching and mixing of concrete.

It has become a common practice in the United States to use precooled concrete for mass concrete when ambient conditions are warm or hot. For dams, this placement temperature has been frequently limited to the average annual air temperature at the project site. The temperature limit was originally intended to ensure that the dam structure was in a low thermal stress condition during its service life. For thermally controlled concrete, ACI 301 originally required the concrete be no warmer than 70°F (20°C) at the time of placement; however, this limit was eventually eliminated and replaced with control of temperatures and temperature differences in the concrete placement, as thermally controlled concrete typically did not have the same restraint considerations as dams.

On some large dams, including Hoover (Boulder) Dam, a combination of precooling and post-cooling to temperatures at or below ambient by embedded pipe loops has been used (U.S. Bureau of Reclamation 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 initial temperature. The maximum temperature of hardening concrete was kept below 75°F (24°C) by means of embedded pipe loops. Post-cooling is sometimes required in gravity and arch dams that contain transverse joints so that transverse joints can

be opened for grouting by cooling the concrete after it has hardened. Post-cooling controls peak temperatures, which also helps in the control of thermal cracking. Post-cooling is increasingly being used in thermally controlled concrete as one way to control the high temperature rise of concrete with high cementitious contents and to reduce time to maintain thermal control measures. ACI 207.4R provides information regarding post-cooling systems.

1.2.7 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. In massive structures, such as 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 SCMs 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, properties of the aggregates, and the timeframe allotted for the strength gain. It has become the practice of some designers of dams to specify the desired strength of mass concrete at later ages, such as at 56 or 90 days or even 1 or 2 years.

CHAPTER 2—DEFINITIONS

Please refer to the latest version of *ACI Concrete Terminology* for a comprehensive list of definitions. Definitions provided herein complement that resource.

mass and thermally controlled concrete—There is currently no universally accepted definition for mass concrete based on specific characteristics of concrete or placements that require control of temperatures and temperature differences. *ACI Concrete Terminology* defines mass concrete as “any volume of structural concrete in which a combination of dimensions of the member being cast, the boundary conditions, the characteristics of the concrete mixture, and the ambient conditions can lead to undesirable thermal stresses, cracking, deleterious chemical reactions, or reduction in the long-term strength as a result of elevated concrete temperature due to heat from hydration”. However, this definition does not provide any definitive guidance with respect to the physical characteristics of mass concrete.

thermally controlled concrete—referred to as mass concrete, or reinforced structural mass concrete (RSMC), is used to generally describe concrete for construction where issues with heat generation for higher design strength requirements can lead to high concrete temperatures during its curing and high risk of thermal cracking. Thermally controlled concrete is typically used to describe concrete that generally has higher cementitious materials content, higher temperature rise, smaller maximum aggregate size, and/or higher or earlier compressive strength requirements relative to traditional mass concrete (Bartojay 2012). These conditions often lead to mixtures having a potential for higher temperature rise than the mixtures typically used for traditional mass concrete.

traditional mass concrete—traditional mass concrete is a term used to generally describe mass concrete for

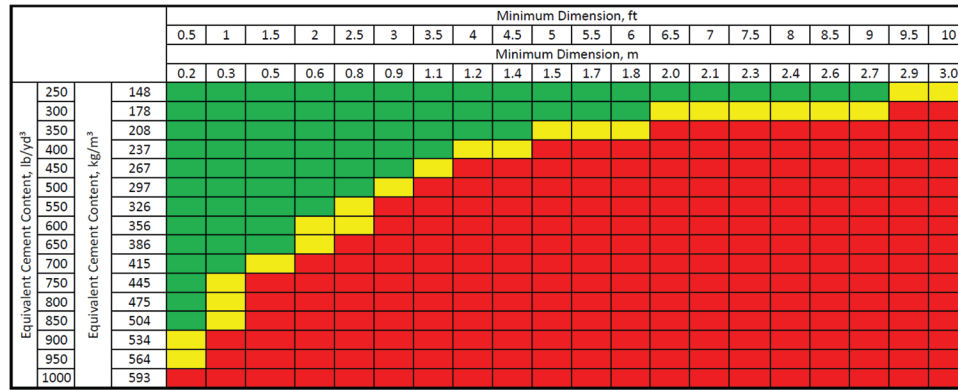


Fig. 3.1.1—Definition of mass concrete as a function of the equivalent cement content of the concrete and placement thickness (Gajda et al. 2018).

construction such as dams where issues with heat generation have been observed with sequential placements having large dimensions that trapped a lot of heat (Bartojay 2012). Traditional mass concrete typically refers to concrete used for these types of placement that generally have a relatively lower cementitious materials content, lower temperature rise, lower or later-age design strength requirements, and/or large maximum coarse aggregate size.

CHAPTER 3—MATERIALS AND MIXTURE PROPORTIONING

3.1—General

As is the case with all concrete, mass concrete is composed of cement, aggregates, water, chemical admixtures, and, frequently, supplementary cementitious materials (SCMs) such as slag cement, fly ash, silica fume, and metakaolin. The objective of mass concrete mixture proportioning is to select the combinations of materials that will produce concrete to meet the requirements of the structure. Economy, workability, dimensional stability, cracking control, low temperature rise, adequate strength, long-term durability, and, in some cases, low permeability, are of utmost importance for mass concrete structures. The limits and requirements for the aforementioned properties will be determined in consideration of the intended service and exposure conditions considered by design. Specific site conditions and construction methods are also taken in consideration when evaluating and selecting materials and proportions for the mass concrete mixture designs.

For smaller projects and those with a few placements of thermally controlled concrete, standard concretes from commercial ready mixed concrete suppliers are often used as the cost and time to develop an optimized concrete mixture for the mass concrete application may not be practical. For larger projects, the efforts to optimize the concrete mixture are often small in comparison to the benefits provided by use of the optimized concrete.

This chapter describes optimized concretes for 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 heavily reinforced structures and tremie placements, among others.

3.1.1 Defining mass concrete by equivalent cement method—When developing a mass concrete mixture, one of the key considerations, in addition to strength and placeability, is the temperature rise of the concrete after placement. For traditional mass concrete, this determines the measures that will be needed to address thermal aspects such as placement height, post-cooling, and the temperature of the concrete at the time of placement. For thermally controlled concrete, this can determine if thermal control of the concrete is required (that is, if measures are necessary to mitigate stresses due to differential temperatures).

Figure 3.1.1 was developed to define mass concrete as a function of the primary influencers; the concrete mixture design and minimum placement dimension (Gajda et al. 2018). It is intended for thermally controlled concrete and not for traditional mass concrete structures with many intertwined placements. This definition can also be used to guide the development of concrete mixtures to reduce efforts needed to control temperatures and temperature differentials, or to develop a concrete mixture for a particular set of placements that does not require thermal mitigation measures. In Fig. 3.1.1, the green areas are not considered mass concrete; the red areas are mass concrete; and the yellow areas are borderline, which indicates that the placement may or may not be mass concrete. In this regard, mass concrete means that the maximum temperature in the placement is anticipated to exceed 160°F (70°C) or the temperature difference within the placement is predicted to exceed 35°F (20°C).

The equivalent cement content (ECC) of the concrete for use with Fig. 3.1.1 can be estimated from Eq. (3.1.1)*

$$\text{ECC} = \text{Cement} + 0.5 \cdot \text{FAsh} + 0.8 \cdot \text{CAsh} + 1.2 \cdot \text{SFMK} + \text{Factor} \cdot \text{Slag} \quad (3.1.1)$$

where Cement is Type I/II portland cement, lb/yd³ (kg/m³); FAsh is Class F fly ash, lb/yd³ (kg/m³); CAsh is Class C fly ash (no distinction is made for the calcium oxide content of the fly ash, which is the main heat generating portion), lb/yd³ (kg/m³); SFMK is silica fume or metakaolin, lb/yd³ (kg/m³); Slag is slag cement (no distinction is made for Grade

100 or Grade 120), lb/yd³ (kg/m³); and Factor is a variable that depends on the percentage of portland cement being replaced by slag cement:

- 1.0 to 1.1 for 0 to 20% replacement;
- 1.0 for 20 to 45% replacement;
- 0.9 for 45 to 65% replacement; and
- 0.8 for 65 to 80% replacement.

3.2—Cements

Economy and low temperature rise can be achieved by reducing the total cementitious materials content and selecting cementitious materials with low heat characteristics. 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 C150/C150M**
- Blended cement*—Types IP, IS, IT, and IL, as covered by **ASTM C595/C595M**
- Hydraulic cement*—Types GU, MS, HS, MH, and LH, as covered by **ASTM C1157/C1157M**

Types I and GU cements are suitable for use in general construction. If these are used alone in mass concrete, they can pose a challenge to control temperature rise of concrete without other measures that can help to control temperature because of their substantially higher heat of hydration.

Types II (moderate heat) and MH cements are preferable for mass concrete construction because they typically have moderate heat of hydration, which is important to control temperature and thus mitigate thermal cracking. Type II cements are designed for moderate sulfate resistance and may have moderate heat properties. Specifications for Type II portland cement require that it contain no more than 8% tricalcium aluminate (C₃A), the compound that contributes substantially to early heat evolution in concrete. Optional specifications for Type II cement place a limit of 100% or less on the sum of 4.75·C₃A and C₃S 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 C150/C150M is reduced due to the slower rate of strength gain associated with the use of this cement.

Type III and Type HE cements, not previously listed, are not generally used in thermally controlled concrete; however, when used for specific applications, they may complicate thermal control efforts because of the high temperature rise associated with these cements.

Types IV and LH, low-heat cements, may be used where it is desired to produce low heat development in massive structures. These cements have been used in limited applications because they have been difficult to obtain and, more importantly, because experience has shown that in most cases, heat development can be satisfactorily controlled by other means. Type IV specification requirements limit the maximum amount of C₃A to 7%, the C₃S to 35%, and place a minimum on the C₂S 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 commercially available in the United States. LH is available in some markets in Canada.

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

Type IP portland-pozzolan cement is a uniform blend of portland cement and fine pozzolan. They are produced either by intergrinding portland cement clinker and pozzolan or by blending portland cement and finely divided pozzolan. The pozzolan constituents can be up to 40% by mass of the portland-pozzolan cement.

Heat of hydration limit of 70 cal/g (290 kJ/kg) at 7 days is an optional requirement for Type IP by adding the suffix (MH). A limit of 60 cal/g (250 kJ/kg) at 7 days is optional for Type IP by adding the suffix (LH).

Type IS portland blast-furnace slag cement is a uniform blend of portland cement and slag cement. It is produced either by intergrinding portland cement clinker and slag cement or by blending portland cement and slag cement. The amount of slag may be up to 95% by mass of the portland-slag cement. This cement has sometimes been used with a pozzolan.

3.3—Supplementary cementitious materials

Supplementary cementitious materials (SCMs) include slag cement, fly ash, natural pozzolans, metakaolin, and silica fume. SCMs are used in mass concrete to reduce the portland cement content; lower internal heat generation and temperature rise (for certain SCMs); improve workability (for certain SCMs); reduce (improve) permeability; and, when applicable, lessen the potential for deleterious expansion caused by alkali-silica reactivity (ASR), delayed ettringite formation (DEF), and sulfate attack. It should be recognized that properties of different SCMs and different sources of the same SCM may vary widely; silica fume and metakaolin have a higher temperature rise than portland cement and reduce workability. Refer to **ASTM C1778**, **ACI 201R**, and **ACI 221R** for more information.

Before an SCM is used, it should be tested in combination with the project cement and aggregates to establish that the SCM will beneficially contribute to the quality and economy of the concrete. In comparison with portland cement, the strength development from certain SCMs may be slow at early ages but continues at a higher level for a longer duration. For the same water-cementitious materials ratio (w/cm), early strength of a concrete containing certain SCMs is generally expected to be lower (with the exception of silica fume and metakaolin) than that of a portland-cement concrete designed for equivalent strength at later ages.

When using SCMs in concrete, the materials are often batched separately at the mixing plant; however, this is not always the case, as blended cements are a combination of interground portland cement and various types of SCM.

ASTM C618 classifies and provides requirements for natural pozzolans (Class N) and fly ash (Class F or C), and

ACI 232.2R addresses the use of fly ash in concrete. Fly ash has been used to replace up to approximately 60% of the portland cement in certain applications, and 50% cement replacement by Class F fly ash has become increasingly common; however, the useful upper limit depends on the chemical composition of portland cement and fly ash. Fly ash particles are typically spherical, which aids in the workability and pumpability of the concrete. The benefit of Class F fly ash in the reduction of the temperature rise of concrete can be seen in Eq. (3.1.1); Class F fly ash has approximately half the heat of hydration as portland cement.

Slag cement is governed by **ASTM C989/C989M**, which specifies three grades based on slag activity index: Grade 80, Grade 100, and Grade 120. The use of slag cement in concrete is discussed in **ACI 233R**. The effect of slag on the temperature rise of concrete depends on the replacement level, as can be seen in Eq. (3.1.1). Slag cement is typically used to replace between 50 and 75% of the portland cement in a mass concrete mixture. Higher replacement levels have been used when specific testing is performed, as performance depends on the specific sources of portland cement and slag cement.

ACI 318 does not permit concretes where the cementitious materials content consists of more than 25% for fly ash or 50% for slag cement to be used in placements exposed to freezing and thawing in the presence of deicer chemicals (Exposure Class F3). This is based on early historical experiences where scaling occurred on some horizontal surfaces with a high SCM content and high w/cm , exacerbated by inadequate curing and/or improper finishing prior to salt exposure. There are many examples of successful high SCM concretes where 75% of the cementitious materials consisted of SCMs. **ASTM C672/C672M**, or similar newer tests such as **CSA A23.2-22C**, can be performed to verify scaling resistance of high-SCM concretes (**Hooton and Vassilev 2012**; **CSA A23.2-22C**).

Silica fume and metakaolin are sometimes used to increase the early-age strength of the concrete and to improve the permeability; however, the inclusion of these materials often requires additional attention to plastic shrinkage cracking and curing. Replacement of portland cement with silica fume, metakaolin, or both, typically increases the temperature rise of concrete as can be seen in Eq. (3.1.1). The use of silica fume is discussed in **ACI 234R**.

3.4—Chemical admixtures

Chemical admixtures provide important benefits to mass concrete in its plastic state by improving workability, increasing slump, reducing water content, delaying setting time, modifying the rate or capacity for bleeding, entraining air, reducing segregation, and reducing rate of slump loss. Chemical admixtures can provide important benefits to mass concrete in its hardened state by allowing concrete proportions to be modified and optimized (to reduce the cementitious content) to produce concrete with lower heat evolution during hardening, increased strength, increased durability, improved permeability, and improved abrasion or erosion resistance. An extensive discussion of admixtures

is contained in **ACI 212.3R** and requirements for chemical admixtures are contained in **ASTM C494/C494M**.

Air-entraining admixtures produce microscopic air bubbles in concrete during mixing, which is needed for freezing-and-thawing resistance. Other benefits of air entrainment include improved workability, reduced segregation, and lessened bleeding. For these reasons, air entrainment is sometimes used even when the structure is not exposed to freezing-and-thawing cycles during its service life. In general, 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. For the same w/cm , an increase in the air content by means of entraining air will generally reduce the strength of concrete. A typical rule of thumb is that each 1% increase in the entrained air content will reduce the strength by 3 to 5%. However, where the cement content is held constant and advantage is taken of the reduced water demand imparted by the entrained air, lower w/cm is achieved. Air entrainment in mass concrete can have a negligible effect on strength. Some of the factors that influence the amount of entrained air in concrete for a given amount of agent include 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, and decreases with increases in amount of fines, temperature of concrete, and mixing time. If fly ash is used that contains high carbon content, an increased dosage of air-entraining admixture is expected to be required. When air-entrained concrete is required, most specifications require the air content to be in the range of 5 to 8%; however, this depends on the coarse aggregate size. Refer to **ACI 301** for specific requirements.

Accelerating admixtures are typically not used in mass concrete because they increase the rate of early heat generation and can pose a challenge in controlling temperature. When high early strength is desired and accelerating admixtures are incorporated in the mass concrete mixture, such as in a tower crane pad, testing should be performed to assess temperature rise and develop a thermal control plan with representative data. Due to its accelerating properties, similar care should be exercised where admixtures containing calcium nitrite, such as in corrosion inhibitors, are used in the concrete.

Water-reducing admixtures are used to reduce the required mixing water for a given workability to increase strength, reduce shrinkage of the concrete, increase the workability of the concrete, or produce the same strength with less cement. Set-controlling or hydration-stabilizing admixtures can be used to keep the concrete in a plastic state longer so that successive layers can be placed and consolidated together before the underlayer sets. Water-reducing admixtures reduce water content by 5% or more. If the water content is kept constant, these admixtures will increase slump instead. Depending on the composition, these admixtures can retard the set time of the concrete but not necessarily reduce the rate of slump loss. Depending on the type of concrete, composition of the cement, temperature, and the quantity and type of chemical admixtures can result in significant increases in

early and later strengths. This gain in strength can be attributed to a reduction in the w/cm and a better dispersion of the cementitious materials throughout the concrete, resulting in a higher degree of hydration.

3.5—Aggregates

Fine and coarse aggregate requirements are governed by **ASTM C33/C33M**. The combined gradation affects the paste content, and smaller maximum aggregate size generally require more paste than larger maximum aggregate size. Additional information on aggregates is contained in **ACI 221R**.

Fine aggregate passes the 3/8 in. (9.5 mm) sieve. It may be composed of natural material (sand), material 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 constituents. ASTM C33/C33M specifies general and widely accepted deleterious material limits in fine aggregate. The specifier should consider the exposure conditions of the

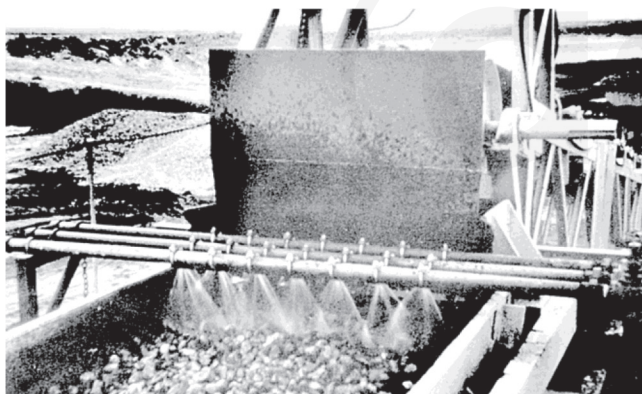


Fig. 3.5a—Coarse aggregate rewashing.

mass concrete and specify deleterious limits deemed appropriate based on severity of environment.

The grading of fine aggregate strongly influences the workability of concrete and strength performance. Sand gradations for mass concrete should be within the limits in ASTM C33/C33M unless laboratory investigation shows other gradations to be satisfactory. Once the proportion is established, the gradation of the fine aggregate should be controlled to avoid variations in the concrete workability.

Each point represents an average of two 18 x 36-in. (450 x 900-mm) and two 24 x 48-in. (600 x 1200-mm) concrete cylinders tested 1 yr for both Grand Coulee and Clear Creek aggregates.

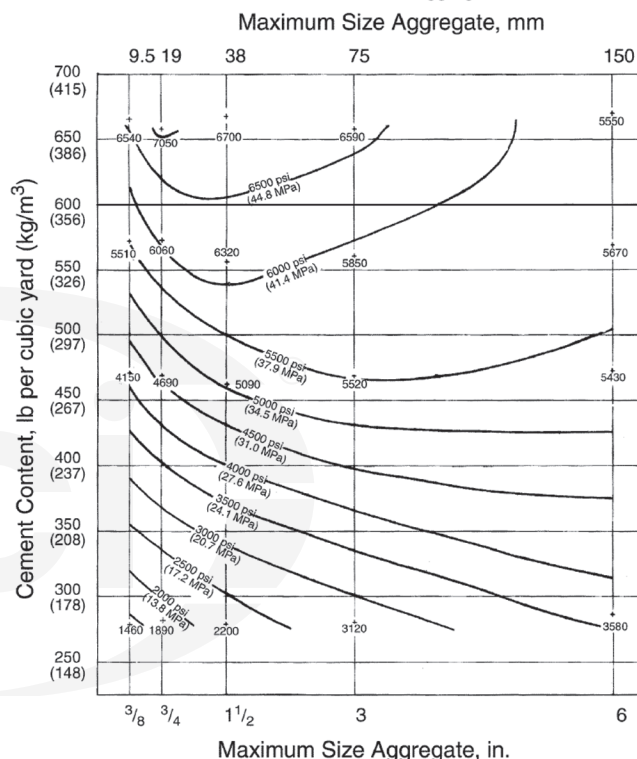


Fig. 3.5b—Effect of aggregate size and cement content on compressive strength at 1 year (adapted from Higginson et al. [1963]).

Table 3.5a—Grading guidance for cobble portion of coarse aggregate gradation (U.S. Bureau of Reclamation 1981)

Test sieve size, square mesh, in. (mm)	Percent by mass passing designate test sieve			
	Cobbles: 6 to 3 in. (150 to 75 mm)	Coarse: 3 to 1-1/2 in. (75 to 37.5 mm)	Medium: 1-1/2 to 3/4 in. (37.5 to 19 mm)	Fine: 3/4 in. to No. 4 (19 to 4.75 mm)
7 (175)	100			
6 (150)	90 to 100			
4 (100)	20 to 45			
3 (75)	0 to 15			
2 (50)	0 to 5			
1-1/2 (37.5)				
1 (25)				
3/4 (19)				
3/8 (9.5)				
No. 4 (4.75)				

Refer to ASTM C33/C33M