Engineering Mass Concrete Structures

By John Gajda, P.E., and Ed Alsamsam, Ph.D., S.E., P.E.

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Concrete Thinking for a sustainable world

PCA Portland Cement Association

Mass concrete is all around us. Traditionally, mass concrete has been associated with dams and other extremely large placements. This is no longer the case. Larger placements for economy and the use of concretes with high cement contents for durability and rapid strength gain mean that an increasing number of concrete placements must be treated as mass concrete.

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Learning Objectives

This article presents a brief summary of mass concrete and provides general guidance on mass concrete specifications and thermal control measures. The reader will learn how to minimize the likelihood of cracking and improve the durability of mass concrete by optimizing the mix design, as well as predicting, monitoring, and controlling concrete temperatures.

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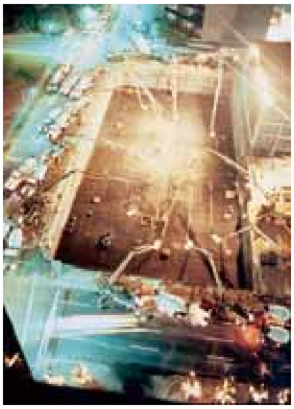
What is mass concrete?

The American Concrete Institute defines mass concrete 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". While the definition is somewhat vague, it is intentionally vague because the concrete mix design, the dimensions, the type of the placement, and the curing methods all affect whether or not cracking will occur.

To put a thickness to the mass concrete definition, we consider mass concrete to be any placement of "normal" structural concrete that has a minimum dimension equal to or greater than 3 feet. Similar considerations should be given to other concrete placements that do not meet this definition but contain Type III cement, accelerating admixtures, and/or cementitious materials in excess of 600 pounds per cubic yard of concrete.



This mass concrete placement of a high-rise building mat foundation takes advantage of cooler nighttime temperatures.

The basics of mass concrete

All concrete generates heat as it cures. The heat is caused by the hydration of the cementitious materials, which is the chemical reaction that provides strength to concrete. Like strength development, the majority of the heat generation occurs in the first few days after placement. For thin items such as pavements, heat energy escapes almost as quickly as it is generated. For thicker sections, specifically mass concrete, the heat cannot escape as quickly as it is generated. The heat is trapped and increases the temperature of the concrete. As the concrete temperature increases, more heat is generated, which further raises the concrete temperature — becoming a vicious cycle. Eventually the concrete begins to cool because there is a finite amount of heat energy in the cementitious materials. The total amount of heat energy depends upon the quantity and type of cementitious materials.

The varying rate of heat generation and dissipation causes the interior of a concrete placement to get hotter than its

Where Mass Concrete Can Be Found

Transit Structures

- Abutments
- Beams
- Girders
- Columns
- Footings
- Column caps

Industrial Facilities

- Tanks and tank foundations
- Blast and fire isolation walls
- Shielding
- Machine foundations

Building Structures

- Shear walls
- Elevator cores
- Foundations
- Mat slabs
- Beams
- Columns
- Transfer girders and slabs

surface. In other words, a temperature difference develops between the interior and the surface. This generates thermal stresses in the concrete (because the interior expands relative to the surface). Cracking immediately occurs when the tensile stress exceeds the tensile strength of the concrete. This cracking is referred to as *thermal cracking*. In most cases, thermal cracking is a durability issue because it provides easy pathways for air and water to reach the reinforcing steel and begin corrosion. In some cases, where thermal stresses are significant, the cracking may affect the structural capacity of the concrete. Thermal cracking takes many forms. On large foundation placements, it may appear as random map cracks. On walls, it may appear as a series of vertical cracks that are widest near the base. On beams, it may appear as uniformly spaced cracks perpendicular to the longest dimension of the beam.

Thermal cracking is one of two primary concerns for mass concrete placements. The other concern results from the concrete getting too hot. High temperatures change the cement hydration reactions. At temperatures above 160 degrees Fahrenheit (°F), unstable hydration products develop in some concretes. This is referred to as *delayed ettringite formation* (DEF). In concretes where DEF occurs, the unstable hydration products can eventually begin to expand within the concrete. This is a long-term effect that may not occur for months or years after the time of construction. In its worst form, DEF can cause significant cracking. To prevent DEF, the rule-of-thumb is to keep the concrete temperature less than 160°F.

While the above discussion provides a very simple overview of DEF (volumes have been written on the subject), the good news is that many concrete placements are relatively immune to the effects of DEF. Such placements include those isolated from water (for example, groundwater, rain, or ponding water) or some that contain cementitious materials with certain resistant chemistry (such as a higher proportion of fly ash or slag cement). Testing can be used to determine if the concrete is susceptible to DEF. Unfortunately, the concrete mix design and cementitious material sources are rarely known until the time of construction. When DEF can be shown to not be a concern, higher temperatures are justifiable; however, temperatures greater than 185°F can reduce the structural properties (strength and modulus of elasticity) of concrete.

Mass concrete specifications

As explained above, the two main concerns with mass concrete placements are the maximum temperature and the maximum temperature difference. Specifications typically limit the maximum temperature to 160°F and the maximum temperature difference to 36°F. Specifications also typically require calculations or a thermal control plan be developed to show that these limits will not be exceeded.

Some specifications also define the length of time these limits will be enforced, place a limit on the temperature at the time of placement, or specify the concrete mix design. These additional requirements are often unnecessary and cause more problems than they solve. In the case of the time limit, this specification can result in thermal cracking if the time period is not long enough. Specifying an initial delivery temperature limit may not be practical in hot-weather

Example of severe thermal cracking on the top surface of a column foundation.

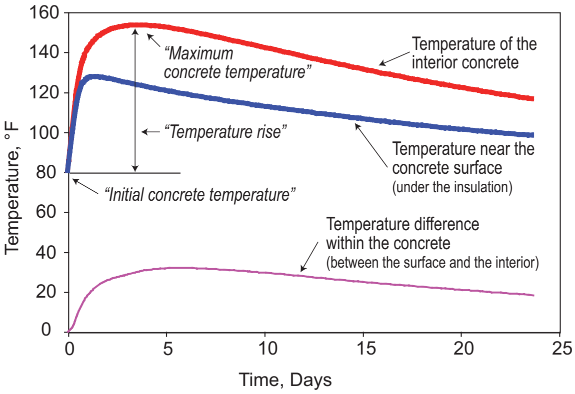
A concrete core removed from a column foundation shows the extent of thermal cracking.

regions or may cause unnecessary expensive precooling of the concrete. Some prescriptive mix design specifications result in a concrete that is not workable or requires the use of materials that are not routinely produced (such as Type IV cement or 6-inch aggregates).

Actually, the often specified temperature difference limit of 36°F is based on outdated literature. Today, concretes are much different, and most placements contain reinforcing steel. While specifying a 36°F temperature difference limit is simple and common, it is only a rule-of-thumb and may not prevent thermal cracking. Some concretes are more tolerant to thermal cracking because they have a high tensile strength or contain aggregates with a low coefficient of thermal expansion. In such cases, higher temperature difference limits may be justifiable. Some have suggested that 45°F is an appropriate temperature difference limit for concrete with granite aggregates, and 56°F for concrete with limestone aggregates. While this may be true, thermal modeling is often required to show that the higher temperature difference limit will control thermal cracking. These analyses typically utilize thermal modeling to define the temperature difference limit so that the thermal stresses do not exceed the tensile strength of the concrete and thermal cracking is prevented. Similar analysis may justify a higher initial temperature at placement. These analyses are often used where the potential construction savings greatly outweigh the cost of the analyses.

Thermal control measures

Many potential solutions exist to minimize efforts needed to control temperature and temperature differences in mass concrete placements. These solutions are often referred to as "thermal controls." Each thermal control has associated costs and benefits. Thermal controls used currently include optimal concrete mix design, insulation, concrete cooling before placement, concrete cooling after placement, and the use of smaller placements.



Modeled temperatures in a 10-foot-thick slab with 600 pounds per cubic yard of cementitious materials (65 percent Type II cement and 35 percent class F fly ash).

Example of the type of cracking that could occur from DEF.

Optimal concrete mix design — Using an optimal concrete mix design is the easiest way to minimize thermal control costs. The following should be considered when working with your ready-mix producer and reviewing a concrete mix design for a mass concrete placement:

- Use low-heat cement. Type II cement (not Type I/II) generally has the lowest heat of hydration. Many cement manufacturers do not provide heat of hydration data in their normal documentation. A 7-day value of 75 cal/g (or less) is desirable.
- The concrete should contain class F fly ash or slag cement. Class F fly ash is typically used to replace 25 to 40 percent of the cement because its heat of hydration is about half that of cement. Class C fly ash may also be used if it has similar low heat of hydration characteristics. Slag cement is often used to replace 50 to 75 percent of the cement, and its heat of hydration is typically 70 to 90 percent of cement. Both fly ash and slag cement decrease the early age strength of the concrete, but can greatly increase the long-term strength. Durability may be a concern in freeze/thaw and chloride-laden environments when high replacement percentages are used. Testing should be performed to verify strength and durability.
- The water-to-cementitious materials ratio of the concrete should be as low as reasonably possible. This increases the efficiency of the cementitious materials (increases the strength-to-heat ratio), and decreases the likelihood of bleeding and segregation. The minimum practical water-to-cementitious materials ratio is on the order of 0.35 to 0.40. Achieving a workable mix at this low water content requires the use of admixtures. Testing is recommended to ensure placeable concrete.
- The total cementitious materials content should be as low as possible to achieve the required compressive strength at the required age (for example, an acceptance age of 42 or 56 days is commonly used in place of 28 days for mass concrete). This will minimize the heat energy and maximum temperature after placement. One potential drawback of using concretes with a reduced cementitious content is that they may be more difficult to pump and place.
- Larger and better graded aggregates reduce the amount of cementitious materials needed to achieve a particular strength. The maximum size of the aggregates depends on the rebar spacing and depth of cover, and should be about three quarters of the smaller of these to avoid honeycombing. For thinner placements, other criteria apply. Aggregates with a maximum size of 1-1/2 inch are commonly available.
- Aggregates such as limestone, granite, or basalt should be used to reduce the thermal expansion and potential for thermal cracking.

It is important to note that not all of these strategies may be cost-effective because of the availability of materials at the project site. In such instances, select the most cost-effective mix design with a low heat energy.

Insulation — While it may seem counter-intuitive to insulate mass concrete, insulation slows the escape of heat, which warms the concrete surface and reduces the temperature difference. In placements with a minimum dimension greater than 5 feet, the use of insulation has virtually no effect on the maximum concrete temperature. Insulation with an R-value in the range of 2 to 4 $hr \cdot ft^2 \cdot °F/Btu$ is typically used to limit the temperature difference. In most cases, concrete insulating blankets are used; however, virtually any insulating material is often acceptable.

To prevent thermal cracking, insulation should be kept in place until the hottest portion of the concrete cools to within the temperature difference limit of the average air temperature. For example, if a 45°F temperature difference is specified and the average air temperature is 20°F, insulation should not be removed until the hottest portion of the concrete cools down to 65°F. This may require that insulation be kept in place up to several weeks (especially on thicker placements). During this time, it may be possible to remove insulation temporarily to perform work. This can be done for a window of time when the temperature difference in the concrete is less than the specified limit.

Concrete cooling before placement — The temperature of delivered concrete is normally about 10°F warmer than the average air temperature. To reduce its temperature, concrete can be precooled prior to placement. As a rule of thumb, every 1°F of precooling reduces the maximum temperature (after placement) by a similar amount.

Chilled water can be used for mix water to precool the concrete by about 5°F. Shaved or chipped ice can be substituted for up to about 75 percent of the mix water to reduce the concrete temperature by up to 15 to 20°F. If extreme precooling is needed, liquid nitrogen (LN2) can be used to precool the concrete mix by any amount (to as low as 35°F). LN2 cooling requires highly specialized equipment to safely cool concrete and can be expensive. However, it is a good option for the contractor as it can be done at the jobsite or at the ready-mix plant.

The cost of the different methods of precooling depends on the local conditions, and the willingness and experience of the concrete supplier.

Concrete cooling after placement — After placement, there is not much that can be done to reduce the maximum temperature of the concrete. Removing insulation only cools the surface, which increases the temperature difference and the likelihood of thermal cracking. To avoid artificially cooling the surface, moisture retention curing methods should be used. Water curing (adding relatively cool water to the warm surface) actually increases the likelihood of thermal cracking. Using heated water for curing is typically not practical and is therefore not recommended.

If installed prior to concrete placement, cooling pipes can be used to remove heat from the interior of the concrete. This increases the cost of construction, but limits the maximum temperature and greatly reduces the time that insulation is required. This method of thermal control is sometimes used on larger projects where an economical

(left) A bridge column uses surface insulation to minimize the temperature difference between the interior and the surface.

(below) Liquid nitrogen cooling is sometimes used to reduce the temperature of the concrete prior to the time of placement.

source of water is available such as a lake or river. Cooling pipes typically consist of a uniformly distributed array of 1-inch-diameter plastic pipes embedded in the concrete. A pipe spacing of 2 to 4 feet-on-center is typical.

Use of smaller placements — Larger sections can often be divided up into several smaller placements. Placing the concrete of a thick foundation in multiple lifts with smaller thicknesses can sometimes be an effective method to minimize the potential for thermal problems. However, the schedule delay between lifts, cost and effort for thermal control of individual lifts, and the horizontal joint preparation may offset the benefits.

Large slabs are sometimes placed as a series of smaller slabs using a checkerboard pattern. Even when placed in this pattern, the thickness of the slabs is not reduced, so the maximum temperature and temperature difference is not reduced. In-fill slabs are subjected to restraint on five sides and cannot expand with the temperature rise of the concrete. Some of the expansion is absorbed by early age creep, and the rest is absorbed as compressive stresses. Upon cooling down, the portion of the expansion absorbed by the early age creep cannot be regained, which results in tensile stresses and an increased likelihood of cracking. To avoid this cracking, careful consideration should be given to slab dimensions by providing a uniform jointing plan to reduce restraint, and allowing for slow and even cooling.

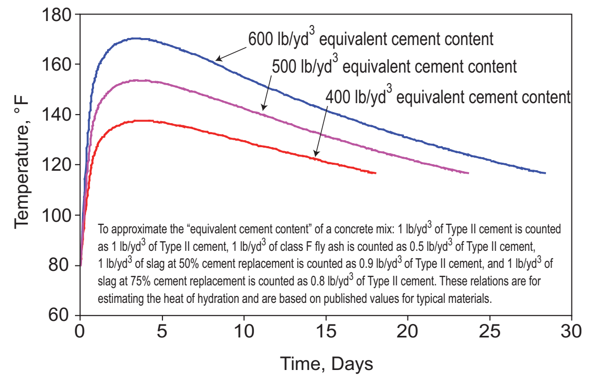
Predicting concrete temperatures

A very simplistic way to estimate the temperature rise of structural concrete is to convert the cementitious content (pounds per cubic yard of concrete) to an "equivalent cement content" then multiply it by 0.14. This provides the temperature rise in degrees Fahrenheit (°F), and is applicable to most placements with a minimum dimension greater than 6 feet for concretes containing Type I or I/II cement. Thinner placements will have a somewhat lower temperature rise. The following approximates the "equivalent cement content" of concrete components (volumes are measured in pounds per cubic yard, lb/yd^3):

- 1 lb/yd^3 of cement is counted as 1 lb/yd^3 cement;
- 1 lb/yd^3 of class F fly ash is counted 0.5 lb/yd^3 cement;
- 1 lb/yd^3 of class C fly ash is counted 0.8 lb/yd^3 cement;
- 1 lb/yd^3 of slag cement (at 50 percent cement replacement) is counted as 0.9 lb/yd^3 cement; and
- 1 lb/yd^3 of slag cement (at 75 percent cement replacement) is counted as 0.8 lb/yd^3 cement.

Adding the temperature rise to the initial concrete temperature provides a prediction for the maximum concrete temperature. In most cases, the concrete is expected to be at or near its maximum temperature within 1 to 3 days after placement. Depending on the minimum dimension, the concrete may not begin to cool for several additional days.

The time of insulation (the time that it will take to cool the concrete to within the temperature difference limit of the average air temperature) can be estimated by assuming that the concrete will cool at a rate of 2°F to 6°F per day (thinner placements cool faster than thicker placements). This provides a very rough estimate because the actual cooling rate depends on the insulation, the dimensions of the placement, and a host of other variables.



Mix designs for a 10-foot-thick slab evaluated by modeling of temperatures.

Monitoring concrete temperatures

Temperature monitoring should be performed to ensure that the thermal control measures are keeping the temperature and temperature differences within the specified limits. Monitoring also provides information so that additional insulation can be added to reduce the temperature difference, if it is too high. Commercially available systems such as Intellirock or plastic-sheathed thermocouples with an appropriate logger can be used to monitor concrete temperatures. At a minimum, concrete temperatures should be monitored at the hottest location in the placement (typically at the geometric center), and at the center of the nearby exterior surfaces (at a depth of 2 to 3 inches below the surface).

Summary

Generally, the concrete mix design is the most effective way to minimize the impact of heat in mass concrete. Cooperation between the designer, specifier, and contractor on mix design, insulation, and cooling is the key to building durable structures successfully with mass concrete. Additional information can be found online at www.massconcretehelp.com and on the Portland Cement Association's website at:
www.cement.org/buildings/mass_splash.asp. ■

John Gajda, P.E., specializes in mass concrete construction and is a principal engineer at CTLGroup in Skokie, Ill. He can be contacted at jgajda@ctlgroup.com. **Iyad M. (Ed) Alsamsam, Ph.D., S.E., P.E.**, is general manager of Buildings and Special Structures at the Portland Cement Association in Skokie, Ill. He can be contacted at alsamsam@cement.org.

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5420 Old Orchard Road, Skokie, IL 60077
(847) 972-9058 • Fax: (847) 972-9059 • Email: info@cement.org • www.cement.org

Quiz questions

1. Thermal control measures should be specified for concrete in which of the following concrete components?

a) 10-foot x 10-foot x 50-inch, 4,000-psi reinforced concrete pump pad foundation
b) 30-inch x 30-inch, 8,000-psi reinforced concrete building column
c) 36-inch, 5,000-psi reinforced concrete floor slab
d) All of the above

2. Thermal control measures should be specified for concrete for which of the following reasons?

a) Control short-term cracks due to thermal stresses
b) Control long-term cracking due to DEF
c) Maximize the durability of the structure
d) All of the above

3. For mass concrete placements, it is important to specify which of the following?

a) Maximum temperature and maximum temperature difference
b) Maximum insulation thickness
c) Minimum cementitious materials content
d) All of the above

4. As the concrete temperature increases, more heat is generated, which speeds hydration and further raises the concrete temperature.

a) True b) False

5. Which of the following strategies can be used to control temperatures and temperature differences in mass concrete?

a) Optimizing the mix design to control heat of hydration
b) Insulating the mass concrete structural elements
c) Cooling the concrete before and after placement
d) All of the above

6. An objectionable temperature difference in a mass concrete placement can be immediately corrected by using which of the following thermal control measures?

a) Installing cooling pipes on the hardened concrete
b) Removing insulation
c) Spray water on the hardened concrete surface
d) Adding insulation

7. Optimizing the mix design for mass concrete placements includes utilizing which of the following?

a) Type II cement
b) Type III cement
c) Accelerating admixtures
d) High early strength concrete

8. Calculate the maximum temperature for a 10-foot-thick mat slab placed during the summer with 90°F concrete, if the concrete contains 450 lbs/yd^3 of Type I cement and 150 lbs/yd^3 of class F fly ash.

a) 153 b) 164 c) 170 d) 174

9. Calculate the maximum temperature for the same slab if the concrete contains 150 lbs/yd^3 of Type I/II cement and 450 lbs/yd^3 of slag cement.

a) 111 b) 143 c) 161 d) 174

10. Assume a peak temperature of 158°F is reached in two days and remains constant for two more days. Then, concrete cools at an average of 2°F/day. If the average air temperature is 80°F and a 36°F temperature difference limit is specified, in how many days can the insulation be permanently removed ?

a) 15 days b) 21 days c) 25 days d) 43 days

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1)	a	b	c	d	6)	a	b	c	d
2)	a	b	c	d	7)	a	b	c	d
3)	a	b	c	d	8)	a	b	c	d
4)	a	b			9)	a	b	c	d
5)	a	b	c	d	10)	a	b	c	d

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