Controlling *Temperatures* in Mass Concrete

Understanding mass concrete is the key to controlling temperatures and ultimately saving time, effort, and money

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Specifications generally limit temperatures in mass concrete to prevent cracking and durability problems. Temperature limits are specified to seemingly arbitrary values of 135 F (57 C) for the maximum allowable concrete temperature and 35 F (19 C) for the maximum allowable temperature difference between the center and surface of the mass concrete section. Typically, the contractor must meet all of the specification requirements, but without a good understanding of mass concrete, keeping concrete temperatures within limits can be a difficult task.

Often, well-established temperature control measures are sufficient to meet project specifications. However, if these are overlooked or poorly understood, they could result in concrete temperatures and temperature differences that greatly exceed specified limits, causing delays to the construction schedule or damage to the concrete. Additionally, recent trends, such as increasing the size of concrete sections and requiring high minimum cement contents or low water-cementitious materials ratios, make temperature control even more difficult.

Understanding mass concrete is the key to controlling temperatures and ultimately saving time, effort, and money.

What is mass concrete?

A question often arises as to exactly what is considered to be mass concrete. According to ACI 116R,[1] mass concrete is defined 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.”

Because this definition doesn’t provide a specific measure, many agencies have developed their own definitions of mass concrete. For example, mass concrete is defined by some agencies as “any concrete element having a least dimension greater than 3 ft (0.9 m).” Under this definition, a large mat foundation with a thickness of 3 ft (0.9 m) would not be considered mass concrete, but a large mat foundation with a thickness of 3.25 ft (1 m) would be considered mass concrete.

Other agencies use different minimum dimensions, ranging from 1.5 to 6.5 ft (0.46 to 2.0 m), depending on past experience. Note that none of these definitions considers the cementitious material content of the concrete. Temperatures within a concrete element will be much different if high-performance or high-early-strength concrete is used rather than typical structural concrete.

Why is temperature control necessary?

All concretes generate heat as the cementitious materials hydrate. Most of this heat generation occurs in the first days after placement.

For thin items such as pavements, heat dissipates almost as quickly as it is generated. For thicker concrete sections (mass concrete), heat dissipates more slowly than it is generated. The net result is that mass concrete can get hot.

Management of these temperatures is necessary to prevent damage, minimize delays, and meet project specifications.

For lack of a standard definition, we consider mass concrete to be any element with a minimum dimension equal to or greater than 3 ft (0.9 m). Similar considerations should be given to other concrete elements that do not meet this definition but contain Type III cement or cementitious materials in excess of 564 lb/yd^3 (335 kg/m^3) of concrete. In many cases, these non-mass elements will also generate significant amounts of heat.

Maximum concrete temperature and temperature difference

Maximum allowable concrete temperatures and temperature differences are often specified to ensure that proper planning occurs prior to concrete placement. In many cases, the specified limits are seemingly arbitrary and do not consider project specifics. As an example of this, certain project specifications limit the maximum concrete temperature to 135 F (57 C), and limit the maximum concrete temperature difference to 35 F (19 C). Other restrictions are often included, such as limits on the maximum and minimum temperatures of delivered concrete.

Maximum concrete temperature

The maximum concrete temperature is limited for a variety of reasons. The primary reason is to prevent damage to the concrete. Studies have shown that the long-term durability of certain concretes can be compromised if the maximum temperature after placement exceeds the range of 155 to 165 F (68 to 74 C). The primary damage mechanism is delayed ettringite formation (DEF). DEF can cause internal expansion and cracking of concrete, which may not be evident for several years after placement.

Other reasons to limit the maximum concrete temperature include reducing cooling times and associated delays, and minimizing the potential for cracking due to thermal expansion and contraction. Temperatures over 190 F (88 C) can also reduce expected compressive strengths.

Maximum temperature difference

A maximum allowable concrete temperature difference is often specified to minimize the potential for thermal cracking. This temperature difference is the difference between the temperature at the hottest portion of the concrete and that at the surface. Thermal cracking will occur when contraction due to cooling at the surface causes tensile stresses that exceed the tensile strength of the concrete.

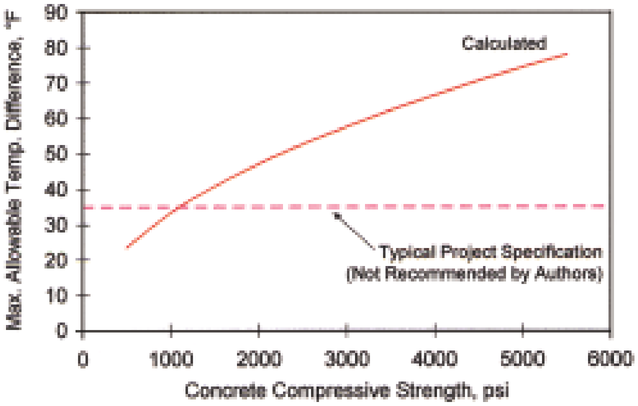

Fig. 1: Comparison of maximum allowable temperature differences

A maximum allowable temperature difference of 35 F (19 C) is often specified in contract documents. This temperature difference is a general guideline based on experience with unreinforced mass concrete placed in Europe more than 50 years ago.

In many situations, limiting the temperature difference to 35 F (19 C) is overly restrictive; thermal cracking may not occur even at higher temperature differences. In other cases, significant thermal cracking may still occur even when the temperature difference is less than 35 F (19 C).

The maximum allowable temperature difference is a function of concrete mechanical properties such as thermal expansion, tensile strength, and elastic modulus, as well as the size and restraints of the concrete element. ACI 207.2R[2] provides guidance on calculating the maximum allowable temperature difference to prevent thermal cracking based on the properties of the concrete and for a specific structure.

Figure 1 compares the typically specified 35 F (19 C) maximum allowable temperature difference with that of the *calculated* maximum allowable temperature difference for a specific mat foundation. As the concrete reaches its design strength, the calculated maximum allowable temperature difference is much greater than 35 F (19 C). Use of the calculated maximum allowable temperature difference can significantly reduce the amount of time that protective measures, such as surface insulation, must be kept in place.

Predicting concrete temperatures

Specifications for mass concrete often require particular cement types, minimum cement contents, and maximum supplementary cementitious material contents. Once this information is available, the process of predicting maximum concrete temperatures and temperature differences can begin. Several options are available to predict maximum concrete temperatures.

A simplistic method is briefly described in a PCA document.[3] This method is useful if the concrete contains between 500 and 1000 lbs of cement per cubic yard of concrete (297 and 594 kg/m³) and the minimum dimension is greater than 6 ft (1.8 m). For this approximation, every 100 lbs (45 kg) of cement increases the temperature of the concrete by 12.8 F (7 C). Using this method, the maximum concrete temperature of a concrete element that contains 900 lb of cement per cubic yard (534 kg/m³) and is cast at 60 F (16 C) is approximately 175 F (79 C). This is above the safe limit for controlling DEF formation. If such a concrete was used, the initial concrete temperature would have to be reduced to 45 F (7 C) to ensure that the maximum concrete temperatures do not exceed 160 F (71 C). This PCA method also does not consider surface temperatures or supplementary cementitious materials.

A more precise method, known as Schmidt's method and described in ACI 207.1R,[4] can be used to predict maximum temperatures and temperature differences for many concrete mix designs and a variety of conditions. CTL staff developed and utilize software based on this method, and have validated it using field calibrations and 12 years of experience. The software can be used to predict maximum concrete temperatures and temperature differences for any concrete mix proportion under almost any placement condition with any commonly utilized means of temperature control. The software is capable of 1-, 2-, and 3-dimensional analyses, depending on the geometry of the structure being analyzed.

Methods of temperature control

Methods of controlling mass concrete temperatures range from relatively simple to complex, and from inexpensive to costly. Depending on a particular situation, it may be advantageous to use one or more methods over another.

Low-heat materials

Different types of cement (and cements within each type) generate varying amounts of heat. Figure 2 presents the typical heats of hydration of different cement types. Type IV cement is not shown because it is rarely available.

Low-heat generating concrete mixtures are always a wise choice for mass concrete to minimize potential thermal problems. Low-heat generating concrete mixes use the maximum allowable level of low-heat pozzolans—such as Class F fly ash or slag—as cement replacements, and the minimum amount of total cementitious materials that achieves the project requirements. Class F fly ash generates about half as much heat as the cement that it replaces and is often used at a replacement rate of 15 to 25%. Ground granulated blast-furnace slag is often used at a replacement rate of 65 to 80% to reduce heat. The reduction in heat generation achieved depends on the concrete temperature, and should be evaluated on a case-by-case basis.

Figure 3 illustrates the effect of Class F fly ash and different cement types on the adiabatic temperature rise of concrete. This is the theoretical increase in temperature of the concrete above the placement temperature, if the concrete is not allowed to cool. In Fig. 3, the total quantity of cementitious materials for all mixes is 525 lb/yd³ (311 kg/m³) of concrete.

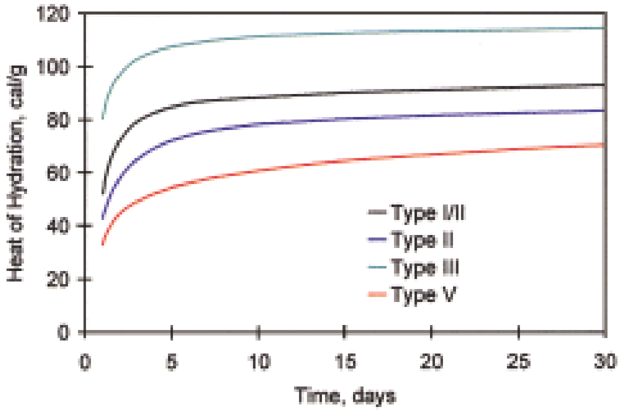

Fig. 2: Heat of hydration for typical cements

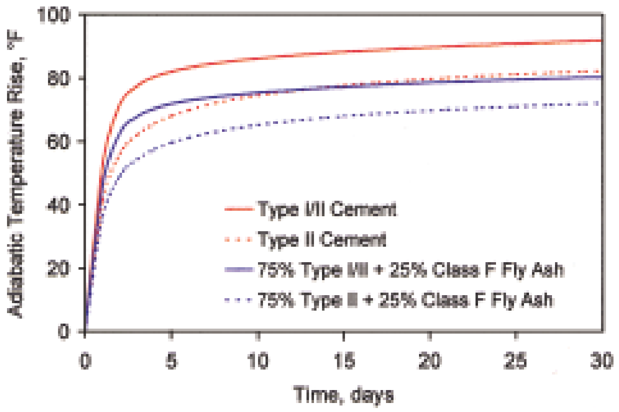

Fig. 3: Concrete temperatures of mixes with 525 lb/yd³ of cementitious materials

Precooling of concrete

The concrete temperature at the time of placement has a great impact on the maximum concrete temperature. Typically, for every 1 F (0.6 C) reduction or increase in the initial concrete temperature, the maximum concrete temperature is changed by approximately 1 F (0.6 C). As an example, to reduce the maximum concrete temperature by approximately 10 F (6 C), the concrete temperature at the time of placement should generally be reduced by 10 F (6 C).

Methods to precool concrete include shading and sprinkling of aggregate piles (as appropriate), use of chilled mix water, and replacement of mix water by ice. Efforts to cool aggregates have the most pronounced effects on the concrete temperature because they represent 70 to 85% of the weight of the concrete.

Liquid nitrogen can also be used to precool concrete or concrete constituents. This option can significantly increase the cost of concrete; however, it has been used to successfully precool concrete to 34 F (1 C) for highly specialized mass concrete placements.

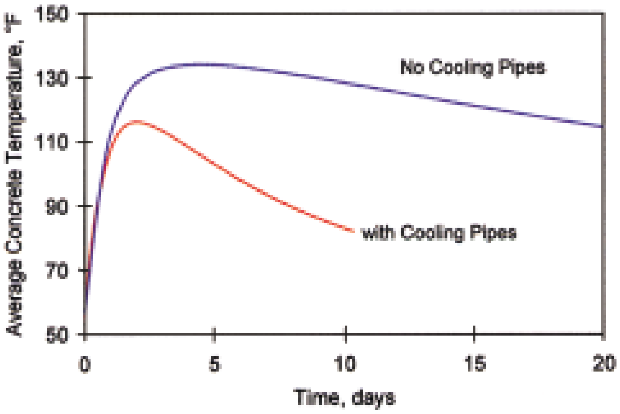

Fig. 4: Effects of internal cooling pipes

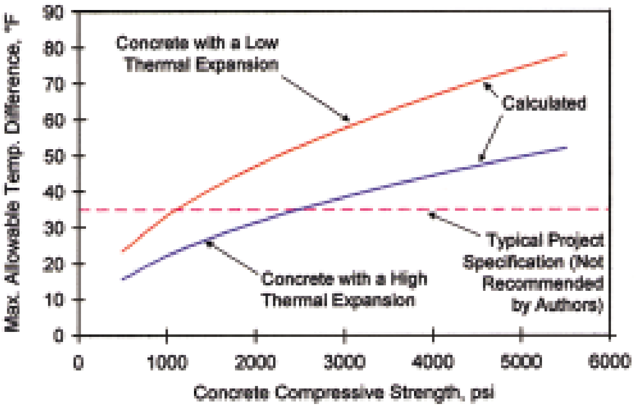

Fig. 5: Effect of aggregate on the maximum allowable temperature difference

Post-cooling of concrete

Cooling pipes in mass concrete are sometimes used to reduce maximum concrete temperatures and to quickly reduce interior temperatures. This method can have high initial and operating costs, but benefits can often outweigh these costs if cooling pipe size, spacing, and temperatures are optimized properly.

Figure 4 illustrates the reduction in the average temperature of a mass concrete pour with and without internal cooling pipes. Note the reduction in the maximum concrete temperature and the increased rate of cooling. It is important to emphasize again that significant internal and surface thermal cracking can result if post-cooling is improperly designed or performed. However, if properly designed, a post-cooling system can significantly reduce concrete temperatures and the amount of time required for cooling.

Surface insulation

Insulation or insulated formwork is often used to warm the concrete surface and reduce the temperature difference, which in turn minimizes the potential for thermal cracking. For most mass pours, surface insulation does not appreciably increase the maximum concrete temperature, but it can significantly decrease the rate of cooling. Insulation is inexpensive, but resulting delays from the reduced cooling rate can be costly. Insulation often has to remain in place for several weeks or longer. Removing it too soon can cause the surface to cool quickly and crack.

Many types of insulation materials are available, and insulation levels can be optimized to meet required temperature differences and maximize the rate of cooling.

Aggregate

Thermal properties of the coarse aggregate can have a significant effect on mass concrete. Concretes containing low-thermal-expansion aggregates such as granite and limestone generally permit higher maximum allowable temperature differences than concretes made using high-thermal-expansion aggregates, as shown in Fig. 5 (Fig. 5 is similar to Fig. 1, except a second calculated maximum allowable temperature difference is added for concrete with a high-thermal-expansion aggregate). This means that selecting an aggregate with a low thermal expansion will reduce the potential for thermal cracking.

References

1. ACI Committee 116, "Cement and Concrete Terminology (ACI 116R-00)," American Concrete Institute, Farmington Hills, Mich., 2000, 73 pp.

2. ACI Committee 207, "Effect of Restraint, Volume Change, and Reinforcement on Cracking of Mass Concrete (ACI 207.2R-95)," American Concrete Institute, Farmington Hills, Mich., 2000, 26 pp.

3. Portland Cement Association, *Design and Control of Concrete Mixtures,* 13th Edition, Skokie, Ill., 1988, 212 pp.

4. ACI Committee 207, "Mass Concrete (ACI 207.1R-96)," American Concrete Institute, Farmington Hills, Mich., 1996, 42 pp.

Selected for reader interest by the editors after independent expert evaluation and recommendation.

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