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Cooling and Insulating Systems for Mass Concrete

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Cooling and Insulating Systems for Mass Concrete

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The need to control volume change induced primarily by temperature change in mass concrete often requires cooling and insulating systems. This report reviews precooling, postcooling, and insulating systems. A simplified method for computing the temperature of freshly mixed concrete cooled by various systems is also presented.

Keywords: cement content; coarse aggregate; creep; formwork; heat of hydration; mass concrete; modulus of elasticity; precooling; postcooling; pozzolan; restraint; specific heat; strain; stress; temperature rise; tensile strength; thermal conductivity; thermal diffusivity; thermal expansion; thermal gradient; thermal shock.

CONTENTS

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CHAPTER 1—INTRODUCTION

1.1—Scope and objective

The need to control volume change induced primarily by temperature change in mass concrete often requires cooling and insulating systems. This report discusses three construction procedures used to control temperature changes in concrete structures: precooling of materials, postcooling of in-place concrete by embedded pipes, and surface insulation. Other design and construction practices, such as selection of cementing materials, aggregates, chemical admixtures, cement content, or strength requirements, are not within the scope of this report.

The objective of this report is to offer guidance on the selection and application of these procedures for reducing thermal cracking in all types of concrete structures.

1.2—Historical background

Major developments in cooling and insulating systems for concrete began with postcooling systems for dams. Later gains were made in developing precooling methods. The use of natural cooling methods has increased with the use of better analytical methods to compute thermal performance. Similarly, insulating systems expanded beyond just cold weather protection and into control of thermal gradients during other weather conditions.

The first major use of postcooling of in-place mass concrete was in the construction of the Bureau of Reclamation's Hoover Dam in the early 1930s. The primary objective was to accelerate thermal contraction of the concrete monoliths within the dam so that the contraction joints could be filled with grout to ensure monolithic action of the dam. Cooling was achieved by circulating cold water through pipes embedded in the concrete. Circulation of water was usually started several weeks or more after the concrete had been placed. Since the construction of Hoover Dam, the same basic system of postcooling has been used in the construction of many large dams and other massive structures, such as powerhouses, except that circulation of cooling water is now typically initiated immediately after placing the concrete.

In the early 1940s, the Tennessee Valley Authority used postcooling in the construction of Fontana Dam for two purposes: to control the temperature rise, particularly in the vulnerable base of the dam where cracking of the concrete could be induced by the restraining effect of the foundation; and to accelerate thermal contraction of the columns so that the contraction joints between columns could be filled with grout to ensure monolithic action. Postcooling was started coincidently with the placing of each lift of concrete. The pipe spacing and lift thickness were varied to limit the maximum temperature to a predesigned level in all seasons. In summer, with naturally high (unregulated) placing temperatures, the pipe spacing and lift thickness for the critical foundation zone was 2.5 ft (0.76 m); in winter, when placing temperatures were naturally low, the pipe spacing and lift thickness for this zone was 5.0 ft (1.5 m). Above the critical zone, the lift thickness was increased to 5.0 ft (1.5 m), and the pipe spacing was increased to 6.25 ft (1.9 m). Cooling was also started in this latter zone coincidently with the placing of concrete in each new lift.

In the 1960s, the Corps of Engineers began the practice of starting, stopping, and restarting the cooling process based on temperatures measured with embedded resistance thermometers. At Dworshak Dam and at the Ice Harbor Additional Power House Units, the cooling water was stopped when the temperature of the concrete near the pipes began to drop rapidly after reaching a peak. Within 1 to 3 days later, when the temperature would rise again to the previous peak temperature, cooling would be started again to produce controlled, safe cooling.

Generally, arch dams were constructed with postcooling systems to expedite the volume change of the mass concrete for joint grouting. The first roller-compacted concrete (RCC) arch dam was Knellpoort Dam in South Africa, completed in 1988. Due to the height and rapid construction of RCC arch dams, design engineers paid close attention to the heat-of-hydration issues due to their effect on the final stress state of the dam. In China, several arch dams have been completed, including Shapai Dam near Chengdu, China, which was the world's highest until 2004. At Shapai Dam, and others since, cooling pipes were embedded between some of the RCC lifts to circulate cool liquid to control the maximum internal temperature of the RCC. Testing showed that high-density polyethylene cooling pipes worked quite well with RCC. The controls and operation procedures for the RCC arch dams were the same as used in conventional concrete dams in the past. By late 2003, 14 RCC arch dams had been completed or were under construction, mainly in China and South Africa.

The first reported use of precooling concrete materials to reduce the maximum temperature of mass concrete was by the Corps of Engineers during the construction of Norfork Dam from 1941 to 1945. A portion of the batch water was introduced into the mixture as crushed ice. Placement temperature of the concrete was reduced by approximately 10°F (6°C). The concrete was cooled as a result of the thermal energy (heat of fusion) required to convert ice to water and from the lowered temperature of the water after melting. Since then, precooling has become very common for mass concrete placements. It also is used for placements of relatively small dimensions, such as for bridge piers and foundations where there is sufficient concern for minimizing thermal stresses.

Injection of cold nitrogen gas into the mixer has been used to precool concrete in recent years. Practical and economical considerations should be evaluated, but it can be effective. As with ice, additional mixing time may be required. Minor amounts of concrete cooling have been achieved by injecting it at transfer points on conveyor delivery systems, in gob hoppers, and in the mixing chamber. Nitrogen's main inefficiency is losing gas to the atmosphere if the mixer or transfer is not well enclosed.

Various combinations of crushed ice, cold batch water, liquid nitrogen, and cooled aggregate are used to lower placement temperature to 50°F (10°C) and, when necessary, to as low as 40°F (4.5°C).

RCC projects have effectively used "natural" precooling of aggregate during production. Large quantities of aggregate

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produced during cold winter months or during cold nighttime temperatures and stockpiled in naturally cold conditions can remain cold at the interior of the pile well into the warm summer months. At Middle Fork, Monksville, and Stagecoach Dams, it was not unusual to find frost in the stockpiles during production of RCC in the summer at ambient temperatures about 75 to 95°F (24 to 35°C). Ice was observed in southern New Mexico's Grindstone Canyon's coarse aggregate stockpile as late as June.

Precooling and postcooling have been used in combination in the construction of massive structures such as Glen Canyon Dam, completed in 1963; Dworshak Dam, completed in 1975; and the Lower Granite Dam Powerhouse addition, completed in 1978.

Insulation has been used on lift surfaces and concrete faces to prevent or minimize the potential for cracking under sudden drops in ambient temperatures. This method of minimizing cracking by controlling rapid cooling of the surface has been used since 1950. It has become an effective practice where needed. The first extensive use of insulation was during the construction of Table Rock Dam, built during 1955 to 1957. More recent examples of mass concrete insulation include the Lock & Dam 26 (Bombich, Norman, and Jones 1987), McAlpine Lock Replacement, and Victoria RCC dam in northern Michigan, constructed in 1992. Insulation of exposed surfaces, for the purpose of avoiding crack development, supplements other control measures during construction, such as precooling materials and postcooling of in-place concrete. A useful practice is to apply surface insulation in layers, such as with multiple blankets, so that the insulation can be removed gradually in warmer weather. Removing all the insulation at once can cause cracking if the air temperature is much lower than the concrete temperature under the insulation.

In addition to reducing thermal stresses, other benefits result from mixing and placing concrete at lower temperatures, such as enhanced long-term durability and strength, improved consistency, and longer placement time. The improved workability can, at times, be used to reduce the water requirement. Cooler concrete is also more responsive to vibration during consolidation.

1.3—Types of structures and temperature controls

Cooling and insulating systems have evolved to meet engineering and construction requirements for massive concrete structures, such as concrete gravity dams, arch dams, navigation locks, nuclear reactors, powerhouses, large footings, mat foundations, and bridge piers. They are also applicable to smaller structures where high levels of internally developed thermal stresses and potential cracks resulting from volume changes cannot be tolerated or would be highly objectionable (Tuthill and Adams 1972; Schrader 1987).

1.4—Construction practices for temperature control

Practices that have evolved to control temperatures and consequently minimize thermal stress and cracking are listed below. Some of these require minimal effort, while others require substantial initial expense:

- Cooling batch water;
- Producing aggregate during cold seasons or cool nights;
- Replacing a portion of the batch water with ice;
- Shading aggregates in storage;
- Shading aggregate conveyors;
- Spraying aggregate stockpiles for evaporative cooling;
- Immersion in cool water or saturation of coarse aggregates, including wet belt cooling;
- Vacuum evaporation of moisture in coarse aggregate;
- Nitrogen injection into the mixture and at transfer points during delivery;
- Using light-colored mixing and hauling equipment, and spraying the mixing, conveying, and delivery equipment with a water mist;
- Scheduling placements when ambient temperatures are lower, such as at night or during cooler times of the year;
- Cooling cure water and the evaporative cooling of cure water;
- Postcooling with embedded cooling pipes;
- Controlling surface cooling of the concrete with insulation;
- Avoiding thermal shock during form and insulation removal;
- Protecting exposed edges and corners from excessive heat loss;
- Cooling aggregates with natural or manufactured chilled air; and
- Better monitoring of ambient and material temperatures.

1.5—Instrumentation

The monitoring of temperatures in concrete components and in fresh concrete can be adequately accomplished with ordinary portable thermometers capable of 1°F (0.5°C) resolution. Recent practice has used thermocouples placed at various locations within large aggregate stockpiles to monitor temperatures in the piles, especially when the aggregate is processed and stockpiled well in advance of when it is used. Postcooling systems require embedded temperature-sensing devices (thermocouples or resistance thermometers) to provide special information for the control of concrete cooling rates. Similar instruments will provide the data to evaluate the degree of protection afforded by insulation. Other instruments used to measure internal volume change, stress, strain, and joint movement have been described (Carlson 1970; USACE 1980).

CHAPTER 2—PRECOOLING SYSTEMS

2.1—General

Minimizing the temperature of the fresh concrete at placement is one of the most important and effective ways to minimize thermal stresses and cracking. Generally, the lower the temperature of the concrete when it passes from a plastic or as-placed condition to an elastic state upon hardening, the lower the tendency toward cracking. In massive structures, each 10°F (6°C) reduction of the placing temperature below average air temperature will lower the peak temperature

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Table 2.1(a)—Water equivalent of 1 yd^3 mass concrete

Ingredient	Batch weight, lb	Specific heat capacity, Btu/lb · °F	Batch heat content, Btu/°F	Water equivalent, lb
Coarse aggregate	2817	0.18	507	507
1% moisture	28	1.00	28	28
Fine aggregate	890	0.18	160	160
5% moisture	45	1.00	45	45
Cement	197	0.21	41	41
Fly ash	85	0.20	17	17
Batched water	139	1.00	139	139
Totals	4201	—	937	937

Table 2.1(b)—Water equivalent of 1 m^3 mass concrete

Ingredient	Batch weight, kg	Specific heat capacity, kJ/kg-K	Batch heat content, kJ/K	Water equivalent, kg
Coarse aggregate	1672	0.75	1254	300
1% moisture	17	4.18	71	17
Fine aggregate	528	0.75	396	95
5% moisture	26	4.18	109	26
Cement	117	0.88	103	25
Fly ash	50	0.84	42	10
Batched water	82	4.18	343	82
Totals	2492	—	2318	555

of the hardened concrete by approximately 4 to 6°F (2 to 3°C) (ACI 207.2R).

A simple example demonstrates how precooling can minimize thermal stresses and cracking. Under most conditions of restraint in mass concrete structures, low levels of stress (or strain) will be developed during and for a short time after the setting of the concrete. The compressive stresses caused by thermal expansion due to the initial high temperature rise are reduced to near zero as a result of a low modulus of elasticity and high creep rates of the early-age concrete. Assuming substantial relaxation continues for some time after final setting during the temperature rise, an idealized condition of zero compressive stress may result when peak temperature is finally reached. Of course, under realistic conditions, the actual stressed state of the structure at peak temperature should be taken into account; however, assuming a state of zero compressive stress at peak temperature will immediately subject the concrete to tension when cooling begins. A concrete placing temperature may be selected to limit resulting tensile strain from exceeding the strain capacity of the concrete during subsequent cooling from peak temperature to the final stable temperature. The procedure is described by the following relationship

$$T_i = T_f + \frac{100 \times C}{e_t \times R} - \Delta t \qquad (2\text{-}1)$$

where

T_i = placing temperature of concrete;
T_f = final stable temperature of concrete;
C = strain capacity (in millionths);
e_t = coefficient of thermal expansion per degree of temperature (in millionths);
R = degree of restraint (in percent) (refer to ACI 207.2R); and
Δt = initial temperature rise of concrete.

The object of the precooling program is to keep temperature T_i low. The designer should know the type and extent of cracking that can be tolerated in the structure. Proper design can accommodate anticipated cracking. When circumstances favor the potential for cracking, provisions should be implemented to deal with cracking. In some cases, it may be more appropriate to allow thermal cracking to develop and then grout or seal the cracks. This might occur, for example, when a large mass of concrete is placed at the base of a deep excavation to act as a dead load to offset uplift pressures. The mass may also become a base for footings and structural concrete that is sufficiently reinforced to resist potential problems due to these cracks.

2.2—Heat exchange

2.2.1 *Heat capacities*—The heat capacity of concrete is defined as the quantity of heat required to raise a unit mass of concrete one degree in temperature. In those systems of units where the heat capacity of water is established as unity, heat capacity and specific heat are numerically the same. The specific heat of concrete is approximately 0.23 Btu/lb °F (0.963 kJ/ kg K); values for components of the mixture range from a low of approximately 0.16 (0.67) for some cements and aggregates to 1.00 (4.18) for water. The temperature of the mixed concrete is influenced by each component of the mixture and the degree of influence depends on the individual component's temperature, specific heat, and proportion of the mixture. Because aggregates comprise the greatest part of a concrete mixture, a change in the temperature of the aggregates will affect the greatest change (except where ice is used) in the temperature of the concrete. Because the amount of cement in a typically lean mass concrete mixture is relatively small, cooling it may not be significant in a temperature control program.

For convenience, the concrete batch and the components of the concrete batch can be considered in terms of a water equivalent, or the weight of water having an equivalent heat capacity. An example of 1 yd^3 of mass concrete and its water equivalent is shown in Table 2.1(a). An example of a 1 m^3 mass concrete mixture and its water equivalent shown in Table 2.1(b).

In other words, 1 yd^3 of this concrete would require the same amount of cooling to reduce (or heating to raise) its temperature 1°F as would be required by 937 lb of water. Similarly, 1 m^3 of this concrete would require the same amount of cooling (or heating) to change its temperature 1°C as would be required by 555 kg of water.

2.2.2 *Computing the cooling requirement*—Assume that a 50°F (10°C) placing temperature will satisfy the design criteria that have been established. From the temperatures of

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the concrete ingredients as they would be received under the most severe conditions, a computation can be made of the refrigeration capacity that would be required to reduce the temperature of the mixture to 50°F (10°C). Using the same mass concrete mixture, the refrigeration requirement per cubic yard can be computed as shown in Table 2.2(a) and (b). The refrigeration required for a 1 m^3 mixture is shown in Table 2.2(b).

If the concrete is mixed under initial temperature conditions in the example, the mixed temperature of the concrete will be

inch-pound units:

$$50\,°\mathrm{F} + \frac{25{,}131\ \mathrm{Btu}}{937\,\mathrm{Btu}/°\mathrm{F}} = 50°\mathrm{F} + 27°\mathrm{F} = 77°\mathrm{F}$$

SI units:

$$10\,°\mathrm{C} + \frac{33{,}910\ \mathrm{kJ}}{2318\ \mathrm{kJ/K}} = 10°\mathrm{C} + 15°\mathrm{C} = 25°\mathrm{C}$$

To lower the temperature of the concrete to 50°F (10°C), it would be necessary to remove 25,131 Btu (26,514 kJ) from the system. The temperature of mixed concrete can be lowered by replacing all or a portion of the batch water with ice or by precooling the components of the concrete. Often one cooling method does not provide enough cooling capacity to meet required temperatures. Examples of limitations that lead to multiple cooling methods include practical limitations to the amount of water can be reasonably replaced with ice, and aggregate stockpiles that have excessive free water that enters the mixture at the aggregate temperature.

2.2.3 *Methods of precooling concrete components*—The construction of mass concrete structures, primarily dams, has led to improved procedures for reducing the initial temperature of the concrete.

Concrete components can be precooled in several ways. The batch water can be chilled, ice added, ice can be substituted for part of the batch water, or a combination of both. Sufficient water needs to be added as water rather than ice, allowing proper introduction of admixtures and reasonable mixing efficiency and times. Also, it is important to realize that ice added to batch water, thereby chilling the batch water, cannot also be considered in the calculation of replacement ice in the mixture. The energy spent melting does not cool the water and the mixture. If the ice is fully melted, its effect on cooling has fully been realized in achieving the batch water temperature. Aggregate stockpiles can be shaded. Aggregates can be processed and stockpiled during cold weather. If the piles are large, only the outside exposed portion will heat up a significant amount when warm weather occurs, preserving the colder interior for initial placements. Fine aggregates can be processed with chilled water using a classifier, sand screw, or dewatering plate vibrator. Methods for cooling coarse aggregates, which often provide the greatest potential for removing heat from the

Table 2.2(a)—Refrigeration requirement per cubic yard

Ingredient	Initial temperature, °F	Degrees to 50°F, °F	Water equivalent, lb	Btus to get to 50°F, Btu
Moist coarse aggregate	75	25	535	13,375
Moist fine aggregate	73	23	205	4715
Cement	120	70	41	2870
Fly ash	73	23	17	391
Batched water	70	20	139	2780
Heat of mixing, estimated				1000
Totals			937	25,131

Table 2.2(b)—Refrigeration requirement per cubic meter

Ingredient	Initial temperature, °C	Degrees to 10°C, °C	Water equivalent, kg	kJ* to get to 10°C, kJ
Moist coarse aggregate	24	14	300	17,556
Moist fine aggregate	23	13	121	6575
Cement	49	39	25	4076
Fly ash	23	13	10	543
Batched water	21	11	82	3770
Heat of mixing, estimated				1390
Totals			538	33,910

*Product of degrees to 10°C × water equivalent × 4.18.

mixture, can include sprinkling stockpiles with water to provide for evaporative cooling, spraying chilled water on aggregates on slow-moving transfer belts, immersing coarse aggregates in tanks of chilled water, blowing chilled air through the batching bins or storage silos, and forcing evaporative chilling of coarse aggregate by vacuum. While the most common and efficient use of nitrogen is to cool the concrete in the mixer, successful cooling of the mixture can result from cooling aggregates with nitrogen and cooling at concrete transfer points. Introduction of liquid nitrogen into cement and fly ash during transfer of the materials from the tankers to the storage silos has also been effective (Forbes et al. 1991), but the overall benefit will be minimal if the amounts of cement and ash used in the mixture are small. Combinations of several of these practices are frequently necessary.

2.3—Batch water

The moisture condition of the aggregates should be considered not only for batching the designed concrete mixture, but also in the heat balance calculations for control of the placing temperature. The limited amount of water normally required for a mass concrete mixture does not often provide the capacity by itself to adequately lower the temperature of the concrete even if ice is used for nearly all of the batch water.

2.3.1 *Chilled batch water*—One lb of water absorbs 1 Btu when its temperature is raised 1°F. Similarly, 1 kg of water absorbs 4.18 kJ when its temperature is raised 1°C. A unit change in the temperature of the batch water has approximately five times the effect on the temperature of the concrete as a unit change in the temperature of the cement or aggregates. This is due to the higher specific heat of water with respect

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to the other materials. Equipment for chilling water is less complicated than ice-making equipment, and it avoids problems that can be encountered with handling and feeding ice to the mixer. Its consideration is always indicated whether solely for chilling batch water or in combination with other aspects of a comprehensive temperature control program, that is, inundation cooling of coarse aggregates, cold classifying of fine aggregate, or postcooling of hardened concrete with embedded cooling coils.

It is practical to produce batch water consistently at 35°F (2°C) or slightly lower. Using the mass concrete mixture discussed previously, chilling the 139 lb (82 kg) of batch water from 70 to 35°F (21 to 2°C) will reduce the concrete temperature by approximately 5°F (3°C).

This can be readily computed by multiplying the mass of batch water in pounds by the number of degrees the water temperature is reduced and dividing the whole by the water equivalent of the concrete. For the illustration mixture, this would be

inch-pound units:

$$\frac{139(\text{lb}) \times (70 - 35\ °\text{F})}{937\,\text{water equivalent (lb)}} = 5.2°\text{F}$$

SI units:

$$\frac{82(\text{kg}) \times (21 - 2\ °\text{C})}{555\,\text{water equivalent (kg)}} = 2.8°\text{C}$$

2.3.2 *Using ice as batch water*—One lb of ice absorbs 144 Btu when it changes from ice to water at the same temperature, approximately 32°F. Similarly, 1 kg of ice absorbs 334 kJ when it changes from ice to water. Consequently, the use of ice is one of the basic and most efficient methods to lower concrete placing temperatures.

The earliest method involved the use of block ice that was crushed or chipped immediately before it was batched. Later methods used either ice flaking equipment, where ice is formed on and scraped from a refrigerated drum that revolves through a source of water, or equipment where ice is formed and extruded from refrigerated tubes and is clipped into small biscuit-shaped pieces as it is extruded. Smaller projects that have not justified the cost of installing ice-making equipment have used commercially purchased ice that was then shaved or crushed. Shaved ice has the benefit of melting faster than crushed ice.

It is important that all of the ice melts before the conclusion of mixing and that sufficient mixing time is allowed to adequately blend the last of the melted ice into the mixture. Where aggregates are processed dry, this may require adding no more than three-fourths of the batch water as ice. Where aggregates are processed wet, there will normally be sufficient moisture on the aggregates to permit almost all of the batch water to be added as ice with just enough water to effectively introduce any admixtures. If the entire 139 lb (63 kg) of batch water in the illustration mixture is added as ice, the effect of the melting of the ice would lower the temperature of the concrete by 21°F (12°C)

inch-pound units:

$$\frac{139(\text{lb}) \times 144(\text{Btu/lb})}{937\text{ water equivalent (lb)} \times (1.0\text{ Btu/lb} \cdot °\text{F})} = 21.4°\text{F}$$

SI units:

$$\frac{82(\text{kg}) \times 334(\text{kJ/kg})}{555\text{ water equivalent (kg)} \times (4.18\,\text{kJ/kg} \cdot \text{K})} = 11.8°\text{C}$$

2.4—Aggregate cooling

Although most rock minerals have a comparatively low unit heat capacity, aggregates comprise the greatest proportion of concrete mixtures. Therefore, the temperatures of the aggregates have the greatest influence on the temperature of the concrete. Under the most severe temperature conditions of construction, the objectives of a comprehensive temperature control program cannot be achieved without some cooling of the concrete aggregates.

2.4.1 *Schedule considerations*—If no temperature control measures are implemented, the average concrete placing temperature will lag behind the average daily ambient temperature. Concrete placed during the spring and early summer will be cooler than the average daily temperature. Concrete placed during the fall and early winter will be warmer than the average daily temperature. Scheduling placements during the nighttime in the summer and during the daytime in the winter can take advantage of cooler and warmer temperatures and supplement other methods of reducing concrete temperature.

2.4.2 *Cold weather aggregate processing*—Generally, on large conventional mass concrete projects, aggregate processing occurs concurrently with concrete production and placement. Projects constructed of RCC have large proportions of the concrete aggregate required to be processed and stockpiled before the commencement of placement operations. The RCC placement almost always occurs at a much faster rate than does aggregate production. Significant aggregate temperature reductions can be realized by processing the aggregate during the cold winter season at locations where a marked winter season occurs. The use of large stockpiles and selective withdrawal of aggregates from the stockpiles can reduce the in-place temperatures of the concrete significantly. Additional thermal considerations for RCC are discussed by Tatro and Schrader (1985, 1992).

This effect, however, may be reduced when aggregate production spans a number of seasons. Aggregate usage should be monitored because it is possible to elevate placement temperatures above average ambient temperatures by using aggregates produced during the hot weather. If the average winter temperature is higher than normal or if early-season production is delayed, the effect of precooling is decreased.

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2.4.3 *Processing fine aggregate in chilled water*—If sequencing and needed production rates permit, and if stockpiling is not necessary, using chilled water in the final washing or classification of the fine aggregate can be an effective cooling method. The effluent water from the classifier is directed to a settling tank to drop out excess fines, and the water is returned to the cooler and then back to the classifier. Fine aggregate is readily cooled by this method; it gains heat quite slowly following wet classification because of the moisture it carries and the possibility for evaporation. By this method, fine aggregate can be consistently produced at temperatures between 40 and 45°F (4 and 7°C).

If the entire 935 lb/yd^3 (554 kg/m^3) of fine aggregate (including moisture) of the illustration mixtures is reduced to 45°F (7°C) from its 73°F (23°C) temperature, the result would be a lowering of the concrete temperature by approximately 6°F (4°C), computed as follows

inch-pound units:

$$\frac{205 \text{ moist F.A. water equivalent (lb)} \times (73 - 45\ °\text{F})}{937 \text{ concrete water equivalent (lb)}} = 6.1°\text{F}$$

SI units:

$$\frac{121 \text{ moist F.A. water equivalent (kg)} \times (23 - 7\ °\text{C})}{555 \text{ concrete water equivalent (kg)}} = 3.5°\text{C}$$

2.4.4 *Sprinkling of coarse aggregate stockpiles*—Misting or sprinkling water onto coarse aggregate stockpiles is an inexpensive but limited means of reducing coarse aggregate temperatures. The amount of cooling that can be obtained depends on the cooling effect of natural evaporation which, in turn, depends on the ambient conditions of temperature, wind, and relative humidity. Adequate drainage should be provided beneath the stockpiles. Only enough water to meet evaporation rates is necessary. In very large stockpiles, only the areas from which material is being withdrawn need to be sprinkled.

If the water sprinkled onto the aggregate is cooler than the aggregate itself, this will provide additional cooling. If the water is warmer than the aggregate, however, the benefit of evaporative cooling may be less than the increased temperature caused by sprinkling with warm water. The intent is to achieve cooling through evaporation from the surface of the aggregate particles, so the practice of flooding aggregate piles with excessive water is not necessary and may reduce the benefits of evaporative cooling. If overwatering is performed with water that is heated by the sun and soaks into the piles at a temperature greater than the internal temperature of the aggregate pile, sprinkling will be harmful rather than beneficial.

2.4.5 *Immersion cooling of coarse aggregate*—One of the most effective ways to cool coarse aggregate is immersion in holding tanks through which chilled water is circulated. The tanks are open at the top with a conical bottom leading to a watertight aggregate discharge gate. The water is piped into and out of the tanks for filling and circulation. The cooling cycle consists of filling the tank with chilled water, dumping the coarse aggregate into the tank, circulating the chilled water through the aggregate, draining water from the tank, and discharging the aggregate from the bottom gate. The aggregate is discharged onto a conveyor belt and fed over a vibrating screen to remove excessive moisture. With this method, using 35°F (2°C) water, even the larger 6 in. (152 mm) top size cobbles for mass concrete can be cooled to approximately 38°F (3°C) with a circulating time of 45 minutes. The complete cycle, however, including filling and discharging, would be approximately 2 hours. Separate tanks, up to 125 tons (113 Mg) capacity, have been used for each size of coarse aggregate.

If the entire 2845 lb (1290 kg) of coarse aggregate (including moisture) of the illustration mixture is reduced to 38°F (3°C) from its 75°F (24°C) temperature, it would result in a lowering of the concrete temperature by approximately 20°F (11°C)

inch-pound units:

$$\frac{507 \text{ moist C.A. water equivalent (lb)} \times (75 - 38\ °\text{F})}{937 \text{ concrete water equivalent (lb)}} = 20.0°\text{F}$$

SI units:

$$\frac{317 \text{ moist C.A. water equivalent (kg)} \times (24 - 3\ °\text{C})}{555 \text{ concrete water equivalent (kg)}} = 12.0°\text{C}$$

2.4.6 *Chilled water spray*—Cooling the coarse aggregate while on the belt conveyor enroute to the batch bins by spraying with cold water is occasionally used to supplement the use of ice in the batch water. This typically requires slowing the speed or increasing the length of the feed belt and incorporating a means to handle the excess water. For practical reasons, the duration of the spray application is usually a few to several minutes, resulting in removal of heat only from near the surfaces of the individual pieces of aggregate. Data on the exact amount of heat removed under specific conditions of belt speed, temperature, and rate of water application are not readily available. On one large mass concrete project, 150 gal. (570 L) of chilled water per ton of coarse aggregate was required (in addition to other precooling techniques) to produce 45°F (7°C) concrete. Waddell (1974) gives data on cooling rates of large-size aggregate.

A system for removing excess water before the discharge into the batch bins is essential. Blowing chilled air through the cool and damp aggregate in the bins will further lower its temperature, but careful control is required to avoid freezing the free water.

2.4.7 *Vacuum cooling of aggregates*—Vacuum cooling of aggregates uses the lower boiling point of water when under less than atmospheric pressure, and the large heat absorptive capacity of water when it changes from liquid to vapor. Fine aggregates and all sizes of coarse aggregates can be effectively cooled by this method. The aggregates should be processed moist or contain sufficient water to absorb the amount of heat desired to extract from the aggregates. Steel

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silos or bins, with capacities from 100 to 300 tons each (91 to 272 Mg) of aggregate exposed to a vacuum of 0.25 in. (6 mm) of mercury, will usually provide for a reduction of initial temperatures of 110°F (43°C) to a final average temperature of 50°F (10°C) over a 45 minute operational cycle.

This method uses the free moisture on the aggregates for the evaporative cooling. The moist aggregates are fed into a pressure vessel that can be sealed at both the top inlet and the bottom outlet. Vacuum is applied from a side chamber by steam-fed diffusion pumps.

Again using the illustration mixture, if the 1% surface moisture carried by the coarse aggregates is evaporated, the temperature of the coarse aggregates will be lowered by approximately 54°F (31°C), or down to approximately 20°F (–7°C)

inch-pound units:

$$\frac{28\ (\text{lb}) \times 1040(\text{Btu/lb})}{535\,\text{moist C.A. water equivalent (lb)} \times 1.0(\text{Btu/lb} \cdot {}^\circ\text{F})} = 54.4^\circ\text{F}$$

SI units:

$$\frac{17\ (\text{kg}) \times 2420(\text{kJ/kg})}{317\,\text{moist C.A. water equivalent (kg)} \times 4.18(\text{kJ/kg} \cdot \text{K})} = 31.0^\circ\text{C}$$

In this illustration, the heat of vaporization of water at 0.25 in. (6 mm) of mercury is approximately 1040 Btu/lb (2420 kJ/kg).

As a result of this cooling of the coarse aggregate, the temperature of the concrete would be lowered by about 31°F (18°C), computed as follows

inch-pound units:

$$\frac{28\ (\text{lb}) \times 1040(\text{Btu/lb})}{937\,\text{concrete water equivalent (lb)} \times 1.0(\text{Btu/lb} \cdot {}^\circ\text{F})} = 31.1^\circ\text{F}$$

SI units:

$$\frac{17\ (\text{kg}) \times 2420(\text{kJ/kg})}{555\ \text{concrete water equivalent (kg)} \times 4.18(\text{kJ/kg} \cdot \text{K})} = 17.7^\circ\text{C}$$

2.4.8 *Liquid nitrogen*—An alternate method for cooling batch water and creating an ice/water mixture employs liquid nitrogen, an inert cryogenic fluid with a temperature of –320°F (–196°C) (CCM 1977). From a cryogenic storage tank located at the batch plant, the liquid gas is injected through lances directly into the batch water storage tank, aggregate, or mixer to lower the temperature as much as practical but above freezing. To promote greater cooling of the concrete, however, liquid nitrogen can be injected into the water in a specially designed mixer just before the water enters the concrete mixer, whereby the liquid nitrogen causes a portion of the water to freeze. The amount of ice produced can be varied to meet different temperature requirements.

Advantages of liquid nitrogen cooling include relative low cost to rent or purchase the equipment system and the ability to prepare the plant for nitrogen cooling within just a few days. This can be advantageous as a supplement to other cooling methods to achieve the reduction in concrete temperature only when necessary.

Liquid nitrogen systems have proven successful on a number of construction projects, particularly where automatic or flexible operation control is beneficial (Beaver 2004). Local availability should be considered, and cooling more than 20°F (11°C) can be difficult and inefficient with nitrogen alone by dramatically increasing mixing times and mechanical problems. Liquid nitrogen has also been injected directly into mixers. This approach typically requires that the mixing time be prolonged and preferably that the mixer is at least partially sealed to minimize the loss of gas to the atmosphere. The extremely cold temperatures that develop and typical longer mixing times create potential for thermal shock cracking and often increase mixer maintenance and repair. Significant safety concerns beyond extremely low temperatures include the quick burst of evaporating nitrogen that displaces available oxygen.

Theoretically, other gases can also be used. Dry ice—the solid phase of carbon dioxide—has also been used on a limited basis by placing blocks in aggregate piles. The block changes from solid to gas without a liquid phase, diffusing throughout the aggregate as cold carbon dioxide.

2.5—Cementitious materials

Cementitious materials used in concrete should be handled dry. If the temperature of the cement is below the dew point of the surrounding atmosphere, moisture can condense and adversely affect the ultimate quality of the cement. As a general rule, the concrete mixture heat balance does not require cooling of the cement to meet the placement temperature requirements. Normally, cement is delivered at a temperature of approximately 130 to 155°F (54 to 68°C). The cement temperature can be increased or decreased a few degrees, depending on the cement handling equipment and procedures used. Even if cement is delivered cooler, the normal procedure for transporting it from tank trucks to silos at the job site is with air. The typical truck compressor heats air to approximately 155°F (68°C), so precooled cement will be reheated to some extent if it is blown into silos by this method. Because cement is such a relatively small portion of mass concrete mixtures, its initial temperature has little effect on the concrete temperature. Also, cooling the cement is not very practical or economical.

2.6—Heat gains during concreting operations

Considerations for temperature control should recognize the heat gain (or loss) of the concrete or the concrete ingredients during batch plant storage, concrete mixing, and transportation and placement of the concrete. The placement of a large mass concrete structure can be visualized as a rapid sequence of procedures, all of which are guided by several overall objectives, not the least of which is to protect the concrete from any avoidable heat gain.

Ingredients can be protected against heat gain at the batch plant by means such as insulation, reflective siding, air conditioning, and circulation of chilled air through coarse aggregates.

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The energy required for the mixing of concrete imparts about 1000 Btu of heat per yd^3 (1380 kJ/m^3) of concrete. Where a project plant is conveniently set up to permit rapid bucket transport and placement, there will be an insignificant temperature gain between mixing and placement of the concrete. To account for delays and inconvenient placements, however, it may be judicious to include in the heat balance computation a small contingency for heat gain between mixing and placement.

Conveyors have become very common for delivering mass concrete from the mixer to the placement. Because there is increased surface area of exposed concrete per unit mass compared to bucket placement, conveyor delivery has much more potential for losing or gaining heat to the atmosphere. Covering conveyors and using fast belt speeds will minimize this problem. Using white covers will minimize absorbed solar energy, as will using insulated covers. On the other hand, introducing cold air or gas such as nitrogen at conveyor transfers and onto covered belts can offset potential heat gain and actually be used to provide minor supplemental cooling.

2.7—Refrigeration plant capacity

The size of the cooling plant required, expressed in tons of refrigeration, is given by

$$\frac{\text{Maximum concrete placing rate}(yd^3/h)\cdot\text{heat to be removed}(Btu/yd^3)}{12{,}000\ Btu/h} \tag{2-2}$$

$$\frac{\text{Maximum concrete placing rate}(m^3/h)\cdot\text{heat to be removed}\ (kJ/m^3)}{12{,}660\ kJ/h}$$

Unless aggregates are stockpiled cold and removed rapidly with minimal exposure to the atmosphere, the average aggregate temperature will tend to follow the annual daily cycle of ambient air temperatures. Therefore, the refrigeration plant capacity should be determined for specific segments of time, such as a week or a month, and for a rate of cooled material consumption. The refrigeration plant may be designed for the cooling of only one material, such as production of ice, or may be divided into various cooling systems for production of ice, chilled water, cooled air, according to heat balance needs. A trial procedure for deriving the amount of ice required to satisfy a given initial temperature of 60°F (16°C) is shown in Table 2.3(a) and (b) for the mixture proportions cited in Section 2.2.1, with 79 lb (36 kg) of ice and 60 lb (27 kg) of chilled water.

2.8—Placement area

During hot weather, precooled concrete can absorb ambient heat, mechanical heat, and solar radiation during placement, which will increase the effective placing temperature and the resulting peak temperature. This increase in temperature can be minimized or eliminated by reducing the temperature in the immediate placing area with fog spray, shading, or both. Placing at night can also reduce the effects of hot weather and radiant heat. The stair-stepped process of placing mass concrete to minimize the exposure of bonding surfaces can also be an effective means to minimize heat gain for placements in hot weather. Stair step placement is the process during placement where one places and consolidates a less-than-full thickness or height lift and immediately return to place on the freshly consolidated concrete before initial set, essentially constructing the placement in a stepped fashion.

Table 2.3(a)—Trial heat balance (in.-lb units)

Ingredient	Temperature as batched, °F	Temperature after mixing, °F	Water equivalent, lb	Heat exchanged, Btu
Coarse aggregate (moist)	25	60	535	8025
Fine aggregate (moist)	73	60	205	2665
Cement	120	60	41	2460
Fly ash	73	60	17	221
Heat of mixing				1000
			Approximately	14,400
Batched water				
Ice	32	144*	79	–11,376
Ice (melted)	32	60	79	–2212
Water (chilled)	35	60	60	–1500
			Approximately	–15,100

*Units of heat required to change 1 lb of ice at 32°F to water at same temperature.

Table 2.3(b)—Trial heat balance (SI units)

Ingredient	Temperature as batched, °C	Temperature after mixing, °C	Water equivalent, kg	Heat exchanged, kJ
Coarse aggregate (moist)	24	16	300	10,032
Fine aggregate (moist)	23	16	121	3540
Cement	49	16	25	3448
Fly ash	23	16	10	293
Heat of mixing				1390
			Approximately	18,700
Batched water				
Ice	0	334*	47	–15,698
Ice (melted)	0	16	47	–3143
Water (chilled)	2	16	35	–2048
			Approximately	–20,900

*Units of heat required to change 1 kg of ice at 0°C to water at same temperature.

CHAPTER 3—POSTCOOLING SYSTEMS

3.1—General

Reducing concrete temperatures may be effectively accomplished by circulating a cool liquid (usually water, a mixture of antifreeze and water, or a brine solution with a lower freezing point than water) through thin-walled pipes embedded in the concrete. Depending on the size of the pipe, volume of fluid circulated, and the temperature of the fluid, the heat removed during the first several days following placement can reduce the peak temperature of the concrete by a significant amount. The postcooling system also accelerates the subsequent heat removal (and accompanying volume decrease) during early ages when the elastic modulus is relatively low.

The radial temperature isotherms developed around each cooling pipe create a complex, nonuniform, and changing thermal pattern. Smaller pipes with colder fluid create a more severe local condition than larger pipes with a less-cold fluid. Under conditions of rapid and intense cooling, localized radial or circumferential cracks could develop. While the concrete is fluid to slightly plastic and before developing a reasonable modulus of elasticity (usually before or near the time of the first peak temperature), no restriction on cooling rate is usually needed. After an initial peak concrete temperature has been experienced, cooling is usually continued until the first of these conditions occur:

a) The concrete cooling rate reaches the maximum that can be tolerated without cracking (Section 3.2);

b) The temperature of the concrete decreases to about 30°F (17°C) below the initial peak value. This is an empirically derived value (Section 3.4.2) generally substantiated by slow strain capacity tests; or

c) The concrete has been cooled to its final stable temperature or an intermediate temperature prescribed by the designer.

The duration of this initial cooling period may be as short as several days or as long as 1 month. Subsequently, the concrete temperature usually will increase again. If the increase is significant, one or more additional cooling periods will be necessary. Experience has shown that supplementary cooling operations can safely reduce the concrete temperatures to below a final stable value or to a point that creates joint openings of ample width to permit grouting, if required. Cooling rates, in degrees per day, for these later periods should be lower than that permitted during the initial period because of the higher modulus of elasticity at later ages.

3.2—Embedded pipe

3.2.1 *Materials*—Aluminum or thin-wall steel tubing, 1 in. (25 mm) nominal outside diameter and 0.06 in. (1.5 mm) wall thickness, has been used successfully for embedded cooling coils. Although this pipe size has been used on many projects, analysis clearly shows that larger-diameter piping would be more effective, even with a cooling liquid with a higher temperature. Plastic and polyvinyl chloride (PVC) pipe may also be used, but they should be heavy duty and suited for the climatic and placing conditions of the project. Couplings of the compression type used to join sections of aluminum or steel tubing should be of the same material or nonconductor sleeves, and gaskets should be provided to avoid the galvanic effect of dissimilar metals. Aluminum tubing has the advantages of light weight and easy installation, but is subject to deterioration and leakage due to reaction with alkalies in the cement. It usually is satisfactory for the typically short cooling period; however, deterioration of the piping can be a problem if the cooling line is to be grouted at a later date. When the expected active cooling period exceeds 3 months, aluminum should not be used. In mass concrete dam construction, there have been no well-documented instances reported where the long-term effects of aluminum tubing deterioration has caused distress in the concrete, but it should not be used where absolute integrity of the pipe over the life of the structure is imperative and possible leakage could be critical.

3.2.2 *Spacing*—For practical reasons, pipe coils are usually placed directly on and tied to the top of the previous, hardened concrete lift. Thus, the vertical pipe spacing typically corresponds to the lift height. A horizontal spacing the same as the vertical spacing will result in the most uniform cooling pattern, but variations may be used. For vertical construction, cooling pipes can be secured to the reinforcing steel.

Figures 4.9 through 4.11 of ACI 207.2R-07 can be used as a guide to establish pipe spacings and the amount of cooling necessary for the temperature control desired.

3.2.3 *Pipe loop layout*—Individual pipe runs may range from 600 ft to approximately 1200 ft in length (183 to 366 m), with 800 ft (244 m) being a target value for design purposes (Waddel 1974). Longer pile runs are less effective because the water warms up in the pipe as heat is transferred and increasingly less heat is transferred along the length of pipe. Splices within the pipe runs should be minimized as much as practical.

Pipe loops served by the same coolant distribution manifold should be approximately the same length so as to equalize the flow and cooling effect.

Cooling pipe tie-down methods need to be positioned to secure the pipes. Special attention should be given to spliced areas to secure couplings from working loose. Tie-down wires or embedded anchors can be positioned in the final lift surface before final set. Pipe clamps with mechanically installed anchors have been used but this method requires the concrete to mature to a sufficient strength for the anchors to work properly. Each pipe loop should be leak-tested before the covering concrete is placed. Each pipe run should include a visual flow indicator on the loop side of the supply or return manifold. To ensure the initiation of cooling at the earliest age, to minimize damage to the emplaced pipe, and help keep the pipe from floating in the fresh concrete, water circulation should be in progress at the time concrete placement begins in the covering lift.

3.2.4 *Repairs during placement*—The pipes can be damaged during concrete placement by the concrete itself, by concrete buckets being dropped on it, by vibrators, and so on. Extra sections of pipe and couplings should be readily available in the event that a pipe is damaged during placement. The freshly placed concrete around the damaged pipe should be removed, the damaged section cut out, and a new section spliced onto the existing undamaged pipe. All of the damaged pipe should be removed so that it will not restrict flow through the pipe.

3.3—Refrigeration and pumping facilities

3.3.1 *Pumping plant*—Pumping plant requirements are determined from the number of pipe coils or loops in operation, which in turn may be established from the lift-by-lift construction schedule. The flow rate for each coil typically is from 4 to 4.5 gal. (15 to 17 L) per minute, for a 1 in. (25 mm) diameter pipe (USBR 1976). This will result in a fluid velocity about four times the minimum necessary to ensure turbulent flow conditions. Turbulent flow within the coil increases the rate of energy transfer between the fluid particles,

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therefore increasing the rate of heat flow by convection. Cooling water used in the system, particularly if from a river or similar untreated source, should be filtered to remove sediment so as to reduce the possibility of system stoppages at bends, constrictions, or control valves. Unless the length of the cooling run is short, flows through the coils should be reversed at least daily, automatically or manually, by valved cross-connections at the pumping plant or at the supply/return manifolds serving each bank of individual pipe coils. Insulating the exposed supply and return pipe runs will help ensure the desired water temperatures at the manifold locations. Sizing of the distribution system segments and head loss allowances should follow customary design procedures.

3.3.2 *Refrigeration plant*—The size and number of refrigeration plant components should be based on the maximum requirements (number of coils in operation at the same time and a coil inlet temperature established by the design criteria) and the need for flexibility over the expected duration of the concrete cooling operations. Chilled water as low as 37°F (3°C) has been used for postcooling. Where lower coolant temperatures are required, a chilled mixture of 70% water and 30% antifreeze (propylene glycol) has been effectively used at 33°F (1°C). Details of compressors, condensers, surge tanks, valves, meters, and other production and control items, for either portable or stationary plant, are mechanical engineering functions not covered in this report.

3.3.3 *Alternative water cooling practices*—Cool water from natural sources, such as wells or flowing streams, may be used as the coolant, provided the supply is adequate, the temperature is reasonably constant, and the water contains only a slight amount of suspended sediment. Manifolds, valves, gauges, and loop bends are particularly vulnerable to stoppages if dirty water is used. Some projects have used PVC pipe for the embedded pipe and circulated water from the local municipal water system (Roush and O'Leary 2005).

Water discharged back into a stream or well will be warmer after circulation through the cooling pipes, and may require permits in conformance with local or national environmental codes. In favorable climates, conventional cooling towers using the evaporative cooling effect rather than refrigeration could be feasible.

3.4—Operational flow control

3.4.1 *Manifolds*—Supply and return headers or riser pipes should be tapped at convenient intervals with fittings for attaching manifolds to serve each bank of cooling coils. Flexible connectors with adapters and universal-type hose couplings are recommended.

3.4.2 *Cooling rates*—Charts or isothermal diagrams showing the expected final stable temperature distribution within the fully cooled structure provide temperature objectives for scheduling coil flow operations. Guidelines for cooling rates have been discussed previously.

When the desired rate of temperature drop is exceeded, postcooling operations in that bank of pipe coils should be interrupted until the temperature rises again. Cooling should be resumed when the concrete temperature exceeds the initial peak temperature and is predicted to continue to increase to unacceptable levels.

Experience has shown that most mass concrete having average elastic and thermal expansion properties can resist cracking if the temperature drop is restricted to 15 to 30°F (8 to 17°C) over approximately a 30-day period immediately following its initial peak (USBR 1976).

3.4.3 *Temperature monitoring*—Concrete cooling should be monitored using instruments installed at representative locations within the concrete, including locations close to each pipe and midway between the pipes. Thermocouples, resistance thermometers, and fiber optic cables have all been used. Vertical standpipes embedded in the concrete and filled with water can also be used to measure the concrete temperature within selected zones. A thermometer is lowered into the stand-pipe to the desired elevation and held there until the reading stabilizes. Water temperatures at supply and return manifolds will also serve as a check on the amount of heat being removed from the concrete.

3.5—Surface cooling

Controlled cooling of the surfaces of a thick or massive concrete structure can be a useful crack-reducing practice (Carlson and Thayer 1959). The objective of surface cooling is to create a steep but tolerable thermal gradient adjacent to the exposed vertical surfaces concurrently with the placing of the concrete, and to maintain the cooling for a minimum of 2 weeks. The optimum period determined theoretically for a typical mass concrete placement is about 3 weeks. By developing an initial zero-stress condition at a low temperature, subsequent tensile strains (and stresses) due to further ambient temperature drops are reduced.

Three construction methods are: 1) circulating refrigerated water within double-walled steel forms left in place for the 3-week period; 2) discharging used cooling water from the bottom of hollow forms for the balance of the 3-week period after being raised for the next lift of concrete; and 3) embedding a near-surface pipe cooling system. The surface should not be cooled at a rate causing surface cracks that may later propagate into the mass concrete, and care should be taken to avoid discharging cooling water over exposed surfaces where staining would be objectionable.

3.5.1 *Forms*—Where noninsulated metal forms are used, some beneficial effects can be achieved by spraying with cold water and by shading.

3.5.2 *Curing water*—Shading and water curing of formed and finished surfaces can be conducted to cool directly, with the added benefit of evaporative cooling, in some regions. On horizontal surfaces, the curing should be controlled so that no water remains on the surface long enough to become warm.

CHAPTER 4—SURFACE INSULATION

4.1—General

Once cement and water interact during mixing, the mixture temperature begins to rise as a result of the hydration of the cementitious materials. With lifts of 5 ft (1.5 m) or higher and lateral form dimensions of approximately 8 to 10 ft (2.4 to 3 m), the temperature rise is essentially adiabatic in

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the central part of the mass of fresh concrete. At the exposed surfaces (formed or unformed), the heat generated is dissipated into the surrounding air at a rate dependent on the temperature differential; therefore, the net temperature rise in the concrete adjacent to the surface (or forms) is less than in the interior. While this results in a gradually increasing temperature gradient from the surface to the interior, little or no stress (and strain) is developed because the concrete is in a plastic state. Generally, lean or mass concrete with a lower cementitious content exhibits only a slight degree of rigidity from 4 to 8 hours after placing, depending on the placing temperature, initial heat control, and cement characteristics. During the next 16 to 20 hours, the cement hydration rate normally increases substantially with the concrete passing from a plastic state to plastic-elastic state until at an age of approximately 24 hours, the concrete begins to act in an elastic manner. During this first day, the modulus of elasticity of the concrete is low and its creep is high, with the net result that the stresses (and strains) are essentially zero. For mass concrete having higher cement contents and higher strength requirements, volume changes and consequent stresses develop much earlier. The resulting stress reduction is less than that for the leaner mixtures.

4.1.1 *Stress development*—Before initial set of concrete, the temperature gradient or thermal change causes little or no stress or strain. As the concrete begins to acquire strength and elasticity, changes in the temperature gradient result in length and volume changes that are partially restrained within the structure itself. Statically balanced tensile and compressive stresses are developed. Refer to the Corps of Engineers guidance on thermal analysis of mass concrete structures (USACE 1997) and ACI 207.2R for a complete discussion of the development of stresses from thermal gradients between internal mass concrete and surface concrete.

4.1.2 *Strength development*—The rate of strength gain is closely related to the time and the temperature at which the hydration is taking place. "Maturity" is the strength versus time and temperature relationship for a given mixture (ACI 228.1R). Measured by compression, tensile splitting, and penetration tests, most conventional mass concrete will exhibit a slight degree of rigidity 4 and 8 hours after placing when mean hydration temperature conditions of 90 and 50°F (32 and 10°C), respectively, exist. Mixtures with high pozzolan and low cement contents that are highly retarded, very cold mixtures, or both, may not develop any rigidity or significant heat from hydration for an extended time, generally on the order of 12 to 24 hours. In extremely cold conditions, however, such as at Revelstoke dam, mixtures with pozzolans and retarder did not develop significant strength for several days. After acquiring initial elasticity, the rate of change in strength development increases substantially over the next 16 to 20 hours, but this can also vary considerably, depending on the particular mixture. Surface cracking caused by temperature gradients between the interior and exterior of a concrete section typically becomes a concern in mass concrete after about 24 hours, but this can vary considerably based on the particular mixture, additives, placing temperature, and climate.

4.1.3 *Temperature gradients*—The development of steep thermal gradients near exposed surfaces during early ages while the modulus of elasticity is very low is usually not a serious condition. Low ambient temperatures during setting and development of early stiffness may indeed be helpful by establishing a steep gradient at an early age while the concrete is in a plastic condition before the concrete responds to stress-strain relationships. After the concrete hardens and acquires elasticity, decreasing ambient temperatures and rising internal temperatures work together to increase the temperature gradient and widen the stress difference between the interior and the surface. On any sectional plane, the summation of internal forces should be zero. This results in a high unit tensile stress in the region of the exposed surfaces and a comparatively low unit compressive stress over the extensive interior areas. Hence, a small temperature increase in the interior will cause a slight increase in compression over a large area, but will also cause a corresponding large increase in tensile stress near the surface to maintain a system of zero total net force.

As the rate of hydration slows, ambient temperature alone becomes the significant load-inducing parameter and becomes most serious at the downward sloping part of the annual temperature cycle. The effect is further intensified by short, abrupt drops in ambient temperatures, which tend to be more prevalent at night and during the fall season.

4.2—Materials

The degree of protection required to avoid or significantly reduce the thermal tensile stresses at concrete surfaces can be determined theoretically and has been demonstrated in practice. A thermal resistance (R-value) of 4.0 h · ft^2 · °F/Btu (0.70 m^2 · K/W) has been found to be effective on many projects in moderate climates. This is provided by a 1 in. (25 mm) thickness of expanded synthetic material, such as polystyrene or urethane, whose thermal conductivity is approximately 0.20 and 0.30 Btu · in./h · ft^2 °F (0.03 to 0.04 W/m · K). The closed-cell structure of this type of material is advantageous in minimizing water absorption and capillarity. Mineral wool blankets are not as effective, usually requiring additional thickness to achieve the same amount of protection. Single-ply polyethylene enclosures that remain sealed and provide a static air space between the outside environment and the concrete surface are usually less effective but more economical.

4.2.1 *Effect of sudden air temperature drop*—The calculated effects on concrete temperatures adjacent to exposed surfaces and to insulation-protected surfaces when subjected to rapid air temperature drops are compared in Table 4.1 and 4.2. Concrete thermal properties used in the calculations were

Density	4160 lb/yd^3 (2470 kg/m^3)
Conductivity	15.8 Btu · in./h · ft^2 · °F (2.28 W/m · K)
Specific heat	0.22 Btu/lb · °F (0.920 J/kg · K)
Diffusivity	0.039 ft^2/h (0.0036 m^2/h)

It was assumed that no heat was being generated within the concrete.

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Table 4.1—Effect of insulation protection of concrete exposed to 28°F (16°C) rapid air temperature drop

Elapsed time, h	Air temperature change, °F (°C)	Concrete temperature changes, °F (°C), at various depths, ft (m)				
		0	1 (0.3)	2 (0.6)	3 (0.9)	6 (1.8)
No insulation						
12	–14 (–8)	–9 (–5)	–2 (–1)	0	0	0
24	–21 (–12)	–16 (–9)	–5 (–3)	–1 (–1)	0	0
48	–28 (–16)	–24 (–13)	–11 (–6)	–4 (–2)	–1 (–1)	0
72	–28 (–16)	–25 (–14)	–15 (–8)	–7 (–4)	–4 (–2)	0
96	–28 (–16)	–27 (–15)	–17 (–9)	–10 (–6)	–5 (–3)	–1 (–1)
R-factor 1.0*						
12	–14 (–8)	–1 (–1)	0	0	0	0
24	–21 (–12)	–3 (–2)	–1 (–1)	0	0	0
48	–28 (–16)	–9 (–5)	–3 (–2)	–1 (–1)	0	0
72	–28 (–16)	–13 (–7)	–6 (–3)	–2 (–1)	–1 (–1)	0
96	–28 (–16)	–15 (–8)	–8 (–4)	–4 (–2)	–2 (–1)	0
R-factor 2.0*						
12	–14 (–8)	0	0	0	0	0
24	–21 (–12)	–1 (–1)	0	0	0	0
48	–28 (–16)	–2 (–1)	–1 (–1)	0	0	0
72	–28 (–16)	–5 (–3)	–2 (–1)	–1 (–1)	0	0
96	–28 (–16)	–7 (–4)	–3 (–2)	–2 (–1)	–1 (–1)	0
R-factor 4.0*						
12	–14 (–8)	0	0	0	0	0
24	–21 (–12)	0	0	0	0	0
48	–28 (–16)	0	0	0	0	0
72	–28 (–16)	0	0	0	0	0
96	–28 (–16)	–1 (–1)	–1 (–1)	0	0	0

*R-value is thermal resistance of insulation in h · ft^2 · °F/Btu.

Table 4.2—Effect of insulation protection of concrete exposed to 40°F (22°C) rapid air temperature drop

Elapsed time, h	Air temperature change, °F (°C)	Concrete temperature changes, °F (°C), at various depths, ft (m)				
		0	1 (0.3)	2 (0.6)	3 (0.9)	6 (1.8)
No insulation						
12	–26 (–14)	–17 (–9)	–4 (–2)	0	0	0
24	–39 (–22)	–30 (–17)	–9 (–5)	–2 (–1)	0	0
48	–40 (–22)	–35 (–19)	–18 (–10)	–4 (–2)	–2 (–1)	0
72	–40 (–22)	–37 (–21)	–22 (–12)	–11 (–6)	–5(–3)	0
96	–40 (–22)	–37 (–21)	–25 (–14)	–14 (–8)	–8 (–4)	–1 (–1)
R-factor 1.0*						
12	–26 (–14)	–2 (–1)	0	0	0	0
24	–39 (–22)	–6 (–3)	–1 (–1)	0	0	0
48	–40 (–22)	–15 (–8)	–5 (–3)	–1 (–1)	0	0
72	–40 (–22)	–19 (–11)	–9 (–5)	–4 (–2)	–1 (–1)	0
96	–40 (–22)	–22 (–12)	–13 (–7)	–6 (–3)	–3 (–2)	0
R-factor 2.0*						
12	–26 (–14)	0	0	0	0	0
24	–39 (–22)	–1 (–1)	0	0	0	0
48	–40 (–22)	–4 (–2)	–1 (–1)	0	0	0
72	–40 (–22)	–8 (–4)	–3 (–2)	–1 (–1)	0	0
96	–40 (–22)	–11 (–6)	–5 (–3)	–2 (–1)	–1 (–1)	0
R-factor 4.0*						
12	–26 (–14)	0	0	0	0	0
24	–39 (–22)	0	0	0	0	0
48	–40 (–22)	–1 (–1)	0	0	0	0
72	–40 (–22)	–2 (–1)	0	0	0	0
96	–40 (–22)	–2 (–1)	–1 (–1)	0	0	0

*R-value is thermal resistance of insulation in h · ft^2 · °F/Btu.

4.3—Horizontal surfaces

Unformed surfaces of concrete lifts are difficult to insulate effectively because of damage from and interference with construction activities. Maximum efficiency of the insulation requires close contact with the concrete—a condition not usually attainable on rough lift surfaces. Neither ponding of water nor layers of sand have proven to be practical systems for intermediate lifts in multiple-lift construction. Mineral or glass wool blankets or batting, 2 to 4 in. (50 to 100 mm) in thickness, and a number of roll-on flexible rubber-type materials now commercially available, provide considerable protection and have been widely used.

Until the next layer of concrete is placed, the need for insulation protection of horizontal surfaces is as great as for formed surfaces, and the insulation should be applied as soon as the concrete has hardened sufficiently to permit access by workers.

In severe climates, the application of insulation may have to be accomplished before when typical worker access is attained.

The insulation should be removed to permit lift surface clean-up, but should be replaced promptly unless the covering lift is to be placed within a few hours.

Bales of hay or straw and thick layers of wet sand can be effective and economical ways to provide longer-term and more thorough lift surface protection. Where setting of the concrete may be delayed, consider placing a layer of plastic on the concrete before placing the hay or straw. The heat capacity of wet sand should be taken into account when initially placed because it can drain heat from the underlying surface during that time and actually increase the concrete thermal gradient. Thus, its temperature at placement should be taken into account.

During the 1997/1998 winter shutdown of RCC placement at Penn Forest Dam, the RCC lift surface was covered with 2 ft (0.6 m) of soil that was spread over the lift surface. The soil cover was in place from early December though late March. Thermocouples were placed in the center of the top RCC lift and at the bottom of the soil cover. Nighttime air temperatures occasionally dropped to approximately10°F (–12°C). The lowest temperature recorded in the top RCC lift was approximately 40°F (4°C). The lowest temperature at the bottom of the soil cover was approximately 35°F (2°C). Following the removal of the soil cover in the spring, the top lift surface was washed three times. There was enough silt in the soil to make cleanup somewhat difficult. Geotextile or plastic placed on the RCC before placing the soil cover might have reduced cleanup efforts.

4.3.1 *Insulation rating*–Acceptable temperature gradients can be maintained during the winter season in moderate climates by the application of insulation with an R-value of

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4.0 h · ft^2 · °F/Btu (0.70 m^2 · K/W). In severe climates, insulation with a R-value of 10.0 (1.76) is recommended. Applying several layers of blankets with lower insulation value is recommended over a single layer of higher-insulation material. This also has the advantage of overlapping the blankets at joints to improve the uniformity of insulation, and it allows gradual removal of the insulation (for example, one layer removed every 10 days). Gradual removal minimizes the problems of thermal shock to the surface when the material is removed.

The provisions of ACI 306R, which cautions against placing concrete on frozen foundations, apply equally to horizontal lift surfaces that are at or below 32°F (0°C). Before placing new concrete, such surfaces should be allowed to warm to 40°F (5°C) or higher so that the maximum differential temperature between the old concrete and the maximum temperature of the fresh concrete due to heat of hydration will not exceed 40°F (5°C). Under rigidly controlled conditions, embedded pipe may be used to circulate warm water to prevent an abrupt change in the concrete temperature gradient and to ensure adequate hydration of the cement in the freshly placed concrete. The amount of heat introduced into the concrete should be the minimum necessary to develop a temperature gradient such that strains will not exceed the strain capacity of the concrete.

4.4—Formed surfaces

Rigid synthetic cellular material in sprayed, board, or sheet form as well as blankets containing closed-cell material can be practical methods of insulating. The closed-cell structure of the material results in very low absorption characteristics, and its strength and elastic properties provide adequate rigidity. Generally, foamed materials of this type are somewhat sensitive to heat at approximately 175°F (80°C), but temperatures of this level are not normally encountered after installation. Most synthetic materials will burn when exposed to open flame, and this is a hazard that should not be overlooked.

4.4.1 *Integral form insulation*—A minimum wood form thickness of 3 in. (75 mm) is necessary to provide the desired level of protection while the forms remain in place. Steel forms offer virtually no insulation protection and should be supplemented with suitable insulation materials before placing concrete. A practical solution is to coat the exterior of reusable steel forms with a spray-on synthetic foam of the necessary thickness.

4.4.2 *Form removal*—Upon removing the forms, either wood or steel, insulation should be promptly installed against the exposed concrete surface. When practical, form removal and insulating should be planned for the warmest time of the day. For unexposed formed surfaces, an alternative procedure is to install insulation on the inside of the forms before concrete placement with wire anchors that will project into the concrete when placed. The insulation then is held in place against the concrete surface when the forms are removed. This method has not been successful on exposed concrete because of surface imperfections caused by the relatively flexible insulation. In no event should the gradual surface temperature drop exceed the values recommended in ACI 306R when protection is removed.

4.5—Edges and corners

Where heat can flow concurrently in two or more directions, rapid temperature drops can occur. This results in the development of tensile strains more quickly at edges and corners than on the sides or tops of the structure. Interior concrete in the vicinity of edges and corners will also be subjected to larger tensile strains sooner than in other portions of the structure.

Increased insulation along the edges and at corners of massive concrete structures has effectively reduced the rate and magnitude of the temperature decline during the cold-weather season. Doubling the insulation thickness (reducing conductance by half over a distance of from 2 to 4 ft (0.6 to 1.2 m) from the concrete edges and corners is a reasonable provision for a structure of moderate size.

4.6—Heat absorption from light energy penetration

During construction of the Libby Dam by the Corps of Engineers, significantly higher temperatures were measured at the top surfaces of lifts protected by a urethane foam insulation when exposed to direct sunlight than when shaded. This phenomena did not occur at Dworshak Dam when such surfaces were protected by layers of black sponge rubber. A limited series of experiments confirmed the conclusion that urethane foam insulation permitted light of some wavelength, probably ultraviolet, to pass through to the concrete surface, where it was converted to heat energy. The tests indicated that a barrier of some type (black polyethylene or aluminum foil) was required to block out the potential light-source energy and avoid augmenting the heat being generated within the concrete.

4.7—Geographical requirements

The period when insulation is required for protection against thermal cracking can depend on the concrete mixture, structure or placement geometry, internal and external restraints, rate of strength gain, and climate and geography. The latter factors of climate and geography should be carefully considered when establishing requirements for applying insulation. For locations considered a severe climate, such as high elevation locations or locations where minimum temperatures frequently drop below freezing, insulation should be applied to concrete placed in the early autumn through late spring. This can be relaxed for more moderate climates. Insulation should be used in locations that experience a sharp increase in the daily temperature fluctuation between summer and fall.

CHAPTER 5—REFERENCES

5.1—Referenced standards and reports

The standards and reports listed below were the latest editions at the time this document was prepared. Because these documents are revised frequently, the reader is advised to contact the proper sponsoring group if it is desired to refer to the latest version.

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207.1R Mass Concrete

207.2R Effect of Restraint, Volume Change, and Reinforcement on Cracking of Mass Concrete

228.1R In-Place Methods to Estimate Concrete Strength

306R Cold Weather Concreting

The above publications may be obtained from the following organization:

American Concrete Institute
P.O. Box 9094
Farmington Hills, Mich. 48333-9094
www.concrete.org

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