Guide to Cold Weather Concreting

Reported by ACI Committee 306
Guide to Cold Weather Concreting

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This document guides specifiers, contractors, and concrete producers through the selection processes that identify methods for cold weather concreting. The objectives of cold weather concreting practices are to: a) prevent damage to concrete due to freezing at early ages; b) ensure that the concrete develops the recommended strength for safe removal of forms; c) maintain curing conditions that foster normal strength development; d) limit rapid temperature changes; and e) provide protection consistent with intended serviceability of the structure. Concrete placed during cold weather will develop sufficient strength and durability to satisfy intended service requirements when it is properly proportioned, produced, placed, and protected.

Keywords: accelerating admixtures; antifreeze admixtures; cold weather concreting; concrete temperature; curing; enclosures; form removal; freezing and thawing; heaters; heating aggregates; insulating materials; maturity testing; protection; strength development.

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CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Introduction
The conditions of cold weather concreting exist when the air temperature has fallen to, or is expected to fall below, 40°F (4°C) during the protection period. The protection period is defined as the amount of time recommended to prevent concrete from being adversely affected by exposure to cold weather during construction. Concrete placed during cold weather will develop sufficient strength and durability to satisfy the intended service recommendations when it is properly proportioned, produced, placed, and protected. The necessary degree of protection increases as the ambient temperature decreases.

Take advantage of the opportunity provided by cold weather to place low-temperature concrete. Concrete placed during cold weather, protected against freezing, and properly cured for a sufficient length of time, has the potential to develop higher ultimate strength (Klieger 1958) and greater durability than concrete placed at higher temperatures. It is susceptible to less thermal cracking than similar concrete placed at higher temperatures.

Refer to ACI 306.1 for cold weather concreting requirements in a specification format. The Mandatory Items Checklist in ACI 306.1 can be used to add appropriate modifications to the contract documents.

This document guides the specifier, contractor, and concrete producer through the recommendations that identify methods for cold weather concreting.

1.2—Scope
This guide discusses general recommendations, concrete temperature during mixing and placing, temperature loss during delivery, preparation for cold weather concreting, protection requirements for concrete with or without construction supports, estimating strength development, methods of protection, curing recommendations, and admixtures for accelerating setting and strength gain including antifreeze admixtures.

The materials, processes, quality-control measures, and inspections described in this document should be tested, monitored, or performed as applicable only by individuals holding the appropriate ACI Certifications or equivalent.

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

\[ M = \text{maturity factor, deg-h} \]
2.2-Definitions


- **carbon monoxide**—a colorless and odorless gas in the exhaust of fossil-fuel heaters and internal combustion engines that can cause dusting of concrete surfaces that are less than 24 hours of age.

- **cold weather**—when air temperature has fallen to, or is expected to fall below, 40°F (4°C) during the protection period; protection period is defined as the time recommended to prevent concrete from being adversely affected by exposure to cold weather during construction.

- **freezing**—the development of solid water ice within the paste that disrupts the paste, causing frost lenses to develop in the paste.

- **hydronic heater**—mobile energy-exchanging system used to heat frozen ground, formwork, or concrete surfaces by pumping heated fluid through closed-circulation tubing and a heat exchanger.

- **liquidus temperature**—the minimum temperature at which all components of a solution can be in a liquid state. Below the liquidus temperature the mixture will be partly or entirely solid.

- **maturity testing**—tests performed to estimate in-place concrete strength using in-place concrete temperature history and strength-versus-temperature history functions derived from tests of concrete with comparable mixture proportions.

- **protection**—the materials and environmental conditions in place to prevent concrete from being affected by exposure to cold weather.

\[ t_a = \text{ambient air temperature, } ^\circ\text{F} \ (\circ\text{C}) \]
\[ t_d = \text{concrete temperature upon delivery to the jobsite, } ^\circ\text{F} \ (\circ\text{C}) \]
\[ T = \text{concrete temperature, } ^\circ\text{F} \ (\circ\text{C}) \]
\[ T_a = \text{coarse aggregate temperature, } ^\circ\text{F} \ (\circ\text{C}) \]
\[ T_c = \text{cement temperature, } ^\circ\text{F} \ (\circ\text{C}) \]
\[ T_d = \text{drop in temperature to be expected during a 1-hour delivery time, } ^\circ\text{F} \ (\circ\text{C}). \] (This value should be added to \( t_d \) to determine the recommended temperature of concrete at the plant after batching.)
\[ T_o = \text{datum temperature, } ^\circ\text{F} \ (\circ\text{C}) \]
\[ T_r = \text{fine aggregate temperature, } ^\circ\text{F} \ (\circ\text{C}) \]
\[ T_w = \text{temperature of added mixing water, } ^\circ\text{F} \ (\circ\text{C}) \]
\[ W_c = \text{saturated surface-dry weight of coarse aggregate, lb (kg)} \]
\[ W_f = \text{saturated surface-dry weight of fine aggregate, lb (kg)} \]
\[ W_m = \text{weight of mixing water, lb (kg)} \]
\[ W_{sw} = \text{weight of free water on coarse aggregate, lb (kg)} \]
\[ W_{fw} = \text{weight of free water on fine aggregate, lb (kg)} \]
\[ \Delta t = \text{duration of curing period at concrete temperature } T, \text{ deg-h} \]

CHAPTER 3—OBJECTIVES, PRINCIPLES, AND ECONOMY

3.1—Objectives

The objectives of cold weather concreting practices are to:

(a) Prevent damage to concrete due to early-age freezing. When no external water is available, the degree of saturation of newly placed concrete decreases as the concrete matures and the mixing water combines with cement during hydration. Additionally, mixing water is lost to evaporation even at cold temperatures. Under such conditions, the degree of saturation falls below the critical saturation. Critical saturation is the level at which a single cycle of freezing can cause damage. The degree of saturation falls below critical saturation at the approximate time the concrete attains a compressive strength of 500 psi (3.5 MPa) (Powers 1962). At 50°F (10°C), most well-proportioned concrete mixtures reach this strength within 48 hours. The temperature of concrete is measured in accordance with ASTM C1064/C1064M.

(b) Ensure that the concrete develops the required strength for safe removal of forms, shores, and reshores, and for safe loading of the structure during and after construction.

(c) Maintain curing conditions that promote strength development without exceeding the recommended concrete temperatures in Table 5.1 by more than 20°F (–7°C) and without using water curing, which may cause critical saturation at the end of the protection period, thus reducing resistance to freezing and thawing when protection is removed (5.1).

(d) Limit rapid temperature changes, particularly before the concrete has developed sufficient strength to withstand induced thermal stresses. Rapid cooling of concrete surfaces or large temperature differences between the exterior and interior region of structural members can cause cracking and can be detrimental to strength and durability. At the end of the required period (Chapter 7), gradually remove insulation or other protection so the surface temperature decreases gradually during the subsequent 24-hour period (7.5).

(e) Provide protection consistent with the durability of the structure during its design life. Satisfactory strength for 28-day, standard-cured cylinders is of no consequence if the structure has surfaces and corners damaged by freezing, dehydrated areas, and cracking from overheating because of inadequate protection, improper curing, or careless workmanship. Similarly, early concrete strength achieved by the use of calcium chloride (CaCl₂) is not serviceable if the concrete cracks excessively in later years because of disruptive internal expansion due to corrosion of reinforcement (11.2). Short-term gains in construction economy on concrete protection should not be obtained at the expense of long-term durability.

3.2—Principles

This guide presents recommendations to achieve the objectives outlined in 3.1(a) through (e). The practices and procedures in this guide stem from the following principles concerning cold weather concreting:

(a) Concrete protected from freezing until it attains a compressive strength of at least 500 psi (3.5 MPa) will not be...
damaged by exposure to a single freezing-and-thawing cycle (Powers 1962). It will mature to its potential strength and will not be damaged, despite subsequent exposure to cold weather (Malhotra and Berwanger 1973). No further protection is necessary unless a minimum strength at a minimum time is specified.

(b) Where a specified concrete strength should be attained in a few days or weeks, planning (including mixture proportion alterations and revisions to construction practice) and protection could be required to maintain the concrete temperature needed to attain the specified strength (Chapters 7 and 8).

(c) Except within heated protective enclosures, little or no external supply of moisture is recommended during cold weather curing (Chapter 10).

(d) Under certain conditions, CaCl₂ should not be used to accelerate setting and hardening because of increased chances of corrosion of metals embedded in concrete (Chapter 11).

Times and temperatures in this guide are not exact values for all situations and should not be used as such. The user should consider the primary intent of these recommendations and use judgment in deciding what is adequate for each particular circumstance.

3.3—Economy

Although cold weather concreting results in extra costs because of potentially lower worker productivity and additional needed products such as insulating blankets, tarping, and heaters, it most likely will also allow a project to stay on schedule. The owner should decide whether the extra costs of cold weather concreting operations are a profitable investment, or if it is more cost-effective to wait for mild weather. Neglecting protection against early freezing could result in immediate destruction or permanently weakened concrete, making it essential that adequate planning, protection from low temperatures, and proper curing are performed with cold weather concreting.

CHAPTER 4—GENERAL RECOMMENDATIONS

4.1—Planning

The general contractor, construction manager, concrete contractor, concrete supplier, specific materials suppliers, testing laboratory representative, and owner or architect/engineer should meet in a preconstruction conference to define what cold weather concreting methods will be used. This document guides the specifier, contractor, and concrete producer through recommendations that identify methods for cold weather concreting.

Plans to protect fresh concrete from freezing and maintain temperatures above recommended minimum values should be made well before freezing temperatures are expected to occur. Equipment and materials such as tarping or blankets should be at the worksite before cold weather is likely to occur.

4.2—Protection during unexpected freezing

During periods not defined as cold weather, such as fall or spring in cold climates or winter in temperate climates, precautions to protect all concrete surfaces from unexpected freezing should be provided for at least the first 24 hours after placement or until the minimum compressive strength is achieved for protection from damage using techniques detailed in Chapter 7. Concrete protected in this manner will be safe from damage by freezing at an early age. However, protection from freezing during the first 24 hours does not ensure a satisfactory rate of strength development, particularly when followed by colder weather. Concrete that will be subjected to applied loads should be continuously protected and cured long enough, and at a temperature recommended by Table 5.1, to produce the strength specified for form removal or structural safety (Chapters 7 and 8).

4.3—Concrete temperature

During cold weather, the concrete temperature during placement should not be lower than the values recommended in Chapter 5. To prevent freezing at early ages, maintain the concrete temperature at or above the recommended placement temperature for the length of time given in Chapter 7. The length of this protection period depends on cement type, dosage of accelerators, and the service conditions defined in 7.4.

The concrete temperature during placement should be near the temperature values in Table 5.1 and should not be higher than these values by more than 20°F (11°C). The recommended minimum placement temperatures given in Table 5.1 apply to normalweight concrete. While placement temperatures of lightweight concrete are equivalent to normalweight concrete, experience indicates that freshly mixed lightweight concrete loses heat more slowly than freshly mixed normalweight concrete. Lightweight insulating concretes lose heat even more slowly. However, when exposed to cold temperatures, some lightweight concretes are still susceptible to damage from surface freezing.

4.4—Temperature records

The surface temperature of concrete determines the effectiveness of protection, regardless of ambient temperature. Therefore, it is desirable to monitor and record the concrete surface temperature. During the surface temperature recording and monitoring process, consider:

(a) Concrete corners and edges are vulnerable to freezing and usually more difficult to maintain at the temperatures given in Table 5.1. Monitor the concrete surface temperature in these areas to evaluate and verify the effectiveness of the protection provided.

(b) Monitor internal temperature of concrete to ensure that excessive heating does not occur (9.8). Expendable thermistors or thermocouples cast in the concrete can be used for internal temperature monitoring.

(c) Inspection personnel should record the date, time, outside air temperature, temperature of concrete as placed, and weather conditions such as calm, windy, clear, or cloudy. Record concrete temperatures at regular time intervals, but
not less than twice per 24-hour period. Include temperatures at several points within the enclosure, and on or in the concrete surface, corners, and edges. There should be a sufficient number of temperature measurement locations to show the range of concrete temperatures throughout the structure. Temperature-measuring devices embedded 2 in. (50 mm) beneath the concrete surface are ideal, but placing thermometers against the concrete under temporary covers of insulating material provides satisfactory accuracy and ease of observation. Such temperature-monitoring devices should be left in place throughout the protection period.

(d) Record maximum and minimum temperature readings in each 24-hour period. Data recorded should show the temperature history of each section of concrete cast. Include a copy of the temperature readings in the permanent job records. Measure the concrete temperature at more than one location in the section cast and use the lowest reading to represent the temperature of that section.

4.5—Heated enclosures

Heated enclosures should be strong enough to be windproof and weatherproof so proper temperatures are maintained at concrete corners, edges, and in thin sections. Combustion heaters should be vented and not used to directly heat or dry the concrete. Fresh concrete surfaces exposed to carbon dioxide (CO$_2$), resulting from the use of salamanders or other direct-fired heaters that exhaust flue gases into an enclosed area, can be damaged by carbonation of the concrete. Carbonation can result in soft surfaces or surface crazing, depending on the concentration of CO$_2$, concrete temperature, and relative humidity. Carbon monoxide (CO), which can result from partial combustion, and high levels of CO$_2$ are hazardous to workers.

Indirect and hydronic heaters, with flue systems directing exhaust gases outside the enclosure area, eliminate carbonation potential inside the enclosed heated area.

Enforce strict fire prevention measures. Fire can destroy the protective enclosures and formwork, and damage the concrete. Concrete can be damaged by fire at any age, but at very early ages, additional damage can occur by subsequent freezing of the concrete before new protective enclosures are provided.

4.6—Slab finishing

If during construction, but after the cold weather protection period, the concrete is likely to be exposed to freezing-and-thawing cycles while saturated, air entrainment may be necessary even though the concrete will not be exposed to freezing-and-thawing cycles in service. Where a hard-troweled finish is specified, the addition of air entrainment may lead to finishing difficulties or problems with blisters, delaminations, or other surface defects. These finishing problems often develop when the total air content is greater than 3 percent (ACI 302.1R). In this case, magnesium finishing tools should be used instead of steel tools. The water-cementitious materials ratio (w/cm) should not exceed the limits recommended in ACI 201.2R, and the concrete should be protected from freezing and thawing for the duration of the protection period. For steel-troweled floor and slab construction, air-entrained concrete should not be specified, and the concrete should be protected from freezing and thawing for the duration of the protection period. New sidewalks and other flatwork exposed to melting snow and cold weather should be air entrained and protected from freezing and thawing for the duration of the protection period.

4.7—Concrete workability

For flatwork in cold weather, low-slump concrete could mitigate problems due to excessive bleed water. During cold weather, bleed water may remain on the surface for extended periods, interfering with or prolonging finishing operations. If bleed water is flowed into the concrete, the resulting surface will have lower strength and be prone to dusting and premature deterioration. During cold weather, proportion the concrete mixture to minimize bleeding. If bleed water is present, wait until it evaporates, or skim it off using a rope, hose, or squeegee before troweling.

CHAPTER 5—TEMPERATURE OF CONCRETE AS MIXED AND PLACED, AND HEATING OF MATERIALS

5.1—Placement temperature

During cold weather, control the concrete mixing temperature as described in 5.2. When placing concrete, the temperature should not fall below the values in Line 1 of Table 5.1. Determine the placement temperature of concrete in accordance with ASTM C1064/C1064M. More massive concrete sections lose heat more slowly than smaller sections. It is beneficial to use low placement temperatures for massive structures (ACI 207.1R). The rate of heat loss increases as the temperature differential between the concrete and ambient temperature increases. Therefore, using concrete with a temperature greater than that given on Line 1 of Table 5.1 does not improve the protection against freezing.

Higher temperatures require more mixing water, increase the rate of slump loss, can cause quick setting, and increase thermal contraction. Rapid moisture loss from exposed surfaces of flatwork can cause plastic shrinkage cracks. Rapid moisture loss can occur from surfaces exposed to cold weather because of the low absolute humidity of the cold air (ACI 302.1R). Cast concrete at a temperature as close as practical to the appropriate value in Table 5.1. The placement temperature should not exceed that given in Table 5.1 by more than 20°F (11°C). Concrete placed at temperatures more than 20°F (11°C) higher than those given in Table 5.1 may be adversely affected by rapid setting, and increased thermal contraction.

If early-age strength is not critical, several admixture combinations can be used to produce a low-temperature admixture system that reduces the liquidus temperature, or freezing point, of the water in a concrete mixture. This practice produces reasonable long-term strengths at curing temperatures lower than those presented in Table 5.1. Korhonen et al. (2004) produced and tested eight admixture combinations that produced satisfactory results for
When the temperature of the aggregate may be taken at 75 percent of the hot mixing water in the drum before, or with the aggregate. Adding the coarse aggregate first helps prevent packing at the end of the mixer. Add the cement after the aggregate. As the final ingredient, place the remaining 25 percent (less hold back) of the hot mixing water into the drum at a moderate rate. Typically, 5 to 20 percent of the mixing water is held back for addition at the placement site. Water with a temperature as high as the boiling point may be used, provided the resulting concrete temperatures are within the limits discussed in 5.2 and no flash setting occurs. When using hot water and an air-entraining admixture, the air content should be tested to verify the effectiveness of the admixture. The air-entraining admixture may lose effectiveness due to contact with hot mixing water. Adding the air-entraining admixture after the water temperature is lowered due to contact with the cooler ingredients may improve its effectiveness.

5.4—Heating aggregates

When aggregates are free of ice and frozen lumps, and air temperatures are moderate, the desired temperature of the concrete during mixing can be reached by simply heating the mixing water. When air temperatures are consistently below 25°F (-4°C), it is usually necessary to also heat the aggregates. Heating aggregates to temperatures higher than 60°F (15°C) is rarely necessary if the mixing water is heated to 140°F (60°C). When the coarse aggregate is dry and free of frost, ice, and frozen lumps, temperatures of freshly mixed concrete recommended in Table 5.1 can be reached by increasing the sand temperature. The temperature of the sand seldom has to be above 105°F (40°C) if the mixing water is heated to 140°F (60°C). Heat aggregates sufficiently to eliminate ice, snow, and frozen lumps. Often, frozen lumps as large as 3 in. (76 mm) survive mixing and remain in the concrete after placing. Using hot water with the purpose of thawing the aggregate during mixing is cautioned because the moisture content of the frozen aggregate is difficult to measure and account for in the mixture proportion. The additional water, from melting frozen aggregate while mixing, adds an unknown volume of water to the mixture. This water increases the w/cm by an unknown amount. Seasonal variations should be considered because average aggregate temperatures can be substantially higher than air temperature during autumn, while the reverse can occur during spring. The temperature of the aggregate may be taken at
the surface, middle, and bottom of the pile and averaged to determine the extent of additional heating measures that should be considered, or the stockpile can be mixed and the temperature taken of the mixed stockpile.

5.5—Steam heating of aggregates

Circulating steam in pipes is recommended for heating aggregates. For small jobs, thaw aggregates by heating them over fire inside culvert pipes. When thawing or heating aggregates by circulating steam in pipes, cover exposed aggregate surfaces with tarpaulins to uniformly distribute the heat and prevent ice crust formation. Heating aggregate using steam jets is the most thermally efficient method, but it may produce troublesome moisture variations. Steam confined in a pipe-heating system avoids difficulties of variable moisture in aggregates, but increases localized hot, dry spots. Wear and corrosion of steam pipes embedded in aggregates eventually causes leaks, which may lead to the moisture variation problem caused by steam jets. Inspect and replace pipes as necessary.

When conditions require thawing substantial quantities of extremely-low-temperature aggregates, steam jets may be the only practicable means of providing the necessary heat. In this case, thaw as far in advance of hatching as possible to reach substantial equilibrium in moisture content and temperature. After thawing, reduce the steam supply to the minimum that prevents further freezing, thereby reducing problems arising from variable moisture content. Under these conditions, control mixing water on an individual batch adjustment basis. Dry, hot air instead of steam has been used to keep aggregates ice-free.

5.6—Overheating of aggregates

Avoid overheating so that spot temperatures do not exceed 212°F (100°C) and the average temperature does not exceed 150°F (65°C) when aggregates are added to the batch. These temperatures are considerably higher than necessary for obtaining desirable temperatures of freshly mixed concrete. Temperature variation in the aggregate may alter the water demand, air entrainment, time of set, and slump of the concrete.

Use extra care when batching the first loads of concrete after a prolonged period of steaming the aggregates in storage bins. Remixing overheated aggregate is beneficial, as it reduces large moisture and temperature differentials, and cools the overheated stockpile. Because aggregates may be overheated, many concrete producers recycle the first few tons of very hot aggregates. Normally, this material is discharged and recycled by placing it on top of the aggregates in the storage bins.

5.7—Calculation of mixture temperature

If the weights and temperatures of all constituents and the moisture content of the aggregates are known, the concrete temperature \( T \) (°F and °C) of the mixture may be estimated from the formula

\[
T = \left(0.22(W_{c} + W_{s} + W_{v}) + T_{c}W_{c} + T_{s}W_{s} + T_{v}W_{v}\right) \div \left(0.22(W_{c} + W_{s} + W_{v}) + W_{c} + W_{s} + W_{v}\right)
\]

(5.7a)

Equation (5.7a) is derived by considering the equilibrium heat balance of the materials before and after mixing and by assuming that the specific heats of the cement and aggregates are equal to 0.22 BTU/(lb·°F) [0.22 kcal/(kg·°C)].

If the temperature of one or both of the aggregates is below 32°F (0°C), the free water will freeze, and Eq. (5.7a) should be modified to consider the heat needed to raise the ice temperature to 32°F (0°C) to change the ice to water and raise the free water temperature to the final mixture temperature. The specific heat of ice is 0.5 BTU/(lb·°F) [0.5 kcal/(kg·°C)] and the heat of fusion of ice is 144 BTU/lb (80 kcal/kg). Modify Eq. (5.7a) by substituting the following expressions for \( T_{c}W_{c} \) or \( T_{s}W_{s} \), or both, depending on whether the fine aggregate or coarse aggregate, or both, are below 32°F (0°C).

For inch-pound units:

- substitute \( W_{c}(0.5T_{c} - 128) \) for \( T_{c}W_{c} \) (5.7b)
- substitute \( W_{s}(0.5T_{s} - 128) \) for \( T_{s}W_{s} \) (5.7c)

For SI units:

- substitute \( W_{c}(0.5T_{c} - 80) \) for \( T_{c}W_{c} \) (5.7d)
- substitute \( W_{s}(0.5T_{s} - 80) \) for \( T_{s}W_{s} \) (5.7e)

In Eq. (5.7b) and (5.7e), the constants 128 and 80 are obtained from the heat of fusion needed to melt the ice, the specific heat of the ice, and the melting temperature of ice.

5.8—Temperature loss during delivery

The Swedish Cement and Concrete Research Institute (Petersons 1966) performed tests to determine the expected decrease in concrete temperature during delivery in cold weather. Studies included revolving drum mixers, covered dump bodies, and open dump bodies. The approximate temperature drop for a delivery time of 1 hour can be computed by using Eq. (5.8a) through (5.8c).

For revolving drum mixers:

\[
T_{d} = 0.25(t_{s} - t_{a})
\]

(5.8a)

For covered-dump body:

\[
T_{d} = 0.10(t_{s} - t_{a})
\]

(5.8b)

For open-dump body:

\[
T_{d} = 0.20(t_{s} - t_{a})
\]

(5.8c)

Proportionally adjust the values from these equations for delivery times greater than or less than 1 hour.
The following examples illustrate the application of these equations:

**Example 1:** Concrete is to be continuously agitated in a revolving drum mixer during a 1-hour delivery period. The air temperature is 20°F (−7°C) and the concrete at delivery should be at least 50°F (10°C). Assuming that Eq. (5.8a) represents this situation best, the temperature drop is

\[ T_d = 0.25(50 - 20) = 7.5°F (4.2°C) \]

Therefore, to make allowance for a 7.5°F (4.2°C) temperature drop, the concrete at the plant should have a temperature of at least (50 + 7.5°F), or approximately 58°F (14°C).

**Example 2:** For the same temperature conditions in Example 1, the concrete is delivered within 1 hour and the drum is not to be revolved except for initial mixing and again briefly at the time of discharge. Assuming that Eq. (5.8b) represents this situation best, the temperature drop is

\[ T_d = 0.10(50 - 20) = 3°F (1.7°C) \]

Therefore, to make allowance for a 3°F (1.7°C) temperature drop, the concrete at the plant should have a temperature of at least (50 + 3°F), or 53°F (12°C).

The advantage of covered-dump bodies over revolving drums suggests that temperature losses can be minimized by not revolving the drum more than necessary during delivery.

**CHAPTER 6—PREPARATION BEFORE CONCRETING**

**6.1—Preparation of surfaces in contact with fresh concrete**

All surfaces to receive concrete and all spaces to be filled with concrete should be free of snow, ice, and standing water before placement.

Preparation before concrete is placed may necessitate a temperature increase of the massive metallic embedments, formwork, supporting materials for slabs-on-ground and other surfaces as specified by the engineer or architect.

There are many techniques for warming massive metallic embedments and supporting materials, including heated enclosures, electric blankets, hydronic heating systems, or other acceptable means.

It may be more effective to heat the air and check its temperature rather than heating the surfaces directly, depending on the complexity of the structure. Heat surfaces of formwork to greater than 10°F (−12°C) (Kozikowski et al. 2014). Metal forms will generally be at the same temperature as the adjacent air, and it is more effective to maintain that air temperature above 10°F (−12°C) rather than to attempt to measure the temperature of the forms themselves.

**6.2—Massive metallic embedments**

Placing concrete in contact with metal embedments, such as steel structural members, can freeze the concrete that contacts the embedment. If the embedment has a large thermal mass, the frozen concrete may not thaw before the bulk of the concrete sets. This may significantly reduce the bond to the embedment and cause low concrete quality adjacent to the embedment. Recent work has shown that most embedments, including bars, do not need to be heated unless the air temperature is below 10°F (−12°C) (Kozikowski et al. 2014). Embedments with a cross-sectional area greater than 4 in.² (2580 mm²) should be heated to above 32°F (0°C). The architect/engineer should identify those portions of the embedment that pose potential problems. Reinforcing bars smaller than No. 18 (No. 57) in size are not considered massive embedments.

The contractor should prepare, as a part of his placement plan, the methodology for determining the temperature of embedments using infrared thermometers or similar devices, and how they will be heated as recommended above.

**6.3—Subgrade condition**

In accordance with ACI 302.1R, slabs should not be placed on a frozen base or subgrade. In addition, no other elements, including grade beams, should be placed on a frozen base or subgrade. Placement of insulation over the subgrade, or provision of heat, is recommended to remove any frost in the soil and to raise the subgrade temperature above 32°F (0°C). An appropriate provision for heat and its duration should be selected based on the frost depth and temperature difference with the air. Once the subgrade is thawed and recompacted, insulation should be placed directly over it to protect it from dropping below 32°F (0°C).

Limit surface temperatures of supporting materials beneath slabs-on-ground and the concrete to a temperature differential of less than 20°F (11°C) to avoid inconsistent setting, rapid moisture loss, delaminations, and plastic shrinkage cracking (Mustard and Ghosh 1979). Concrete placed in these conditions could create finishing difficulties due to differential concrete setting rates throughout the slab thickness. To mitigate the finishing difficulties, the contractor can delay finishing operations, use lighter finishing equipment, and take steps to prevent moisture evaporation.

**CHAPTER 7—PROTECTION AGAINST FREEZING FOR CONCRETE NOT REQUIRING CONSTRUCTION SUPPORTS**

The plan for protecting concrete against freezing varies based on the type of loads the element will incur prior to reaching design strength. Concrete elements that do not use construction supports are those elements that will not be needed for significant structural performance during the construction schedule that would otherwise be delayed by lack of design strength due to temperatures below 40°F (4°C). Some common examples of these elements include slab-on-ground systems such as roads, driveways, sidewalks, patios, and slabs, as well as many foundation walls and footings.

**7.1—Protection methods**

Protect concrete from freezing as soon as practicable after placement, consolidation, and finishing without marring or damaging the finished surface. This protection can be
provided by concrete mixture acceleration, insulation, heat systems, enclosures, or a combination of these practices, and should be planned before placement. Accelerating the concrete mixture can include the use of accelerating chemical admixtures (ASTM C494/C494M, Types C and E), decreasing the w/cm, increasing the cement content, reducing the pozzolan content, changing the pozzolan type, or replacing the Type I (general-use) cement with Type III (high-early-strength) cement. Accelerating the strength gain of the concrete mixture should increase the heat of hydration.

7.2—Protection period

Effective protection allows the concrete to gain strength and prevents the concrete from early-age damage by freezing the mixing water. Concrete can resist the effects of one freezing-and-thawing cycle as long as it is air-entrained, not exposed to an external water source, and has reached a compressive strength of approximately 500 psi (3.5 MPa) (Powers 1962; Hoff and Buck 1983).

To ensure that the concrete has reached 500 psi (3.5 MPa), protect the concrete temperature as described in Table 5.1 for the time periods in Line 1 of Table 7.2.

A method of monitoring in-place compressive concrete strength gain is to instrument the structure with temperature-monitoring devices and employ the maturity method (Chapter 8). Keep the protection in place until the desired maturity of sufficient time and temperature has provided the recommended strength. Take care to place the temperature probes near the corners or edges of the member where ambient temperature influence is most critical.

7.3—Protection period for durability

Hydration of the cementitious fraction is needed to develop properties relating to durability, such as strength. If repeated exposure to freezing and thawing is anticipated, reaching 500 psi (3.5 MPa) is not sufficient protection. Concrete with a compressive strength less than 3500 psi (24.5 MPa) and exposed to repeated freezing-and-thawing cycles while critically saturated may be damaged. Consider the addition of air entrainment in the concrete (Table 4.1 of ACI 201.2R) and monitoring the concrete strength gain so that 3500 psi (24.5 MPa) is reached before the protection is removed. Caution is advised for air-entrained concrete that is to receive a burnished or hard-trowel finish (4.6). In these cases, continue protection to prevent damage from repeated freezing-and-thawing cycles when critically saturated.

Concrete intended to provide low permeability or high resistance to chloride ion ingress, identified in the contract documents as being Exposure Class F3, C2, or P1 as defined by ACI 318, should be protected from freezing until the mixture design compressive strength has been achieved.

7.4—Protection for strength gain

If early-age strength is specified, it may be necessary to extend the protection period beyond the minimum duration given in Table 7.2. If early-age strength is not specified, maintain the concrete at temperatures in Table 5.1 for the time period shown in Table 7.2. If early-age strength is specified, main-

<table>
<thead>
<tr>
<th>Table 7.2—Length of protection period for concrete placed during cold weather</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Line</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
</tbody>
</table>

*A day is a 24-hour period.*

tain the element at the temperatures in Table 5.1 until the recommended strength is reached. The duration of protection depends on the concrete mixture proportions, expected construction loads, and the environmental conditions the member will be exposed to during the curing period. Four defined service conditions impact the recommended protection period:

1. **No load, not exposed**: Elements will not be exposed to freezing-and-thawing cycles in service, carry significant loads during the curing period, or both (Line 1 of Table 7.2). Examples of this condition include foundations and substructures that are not subject to early load and, because they are buried deep within the ground or are backfilled, will undergo little or no freezing-and-thawing cycles in service.

2. **No load, exposed**: Elements will not carry significant loads during the curing period and will be exposed to freezing-and-thawing cycles in service (Line 2 of Table 7.2). Examples of this condition include massive piers, dams, and some walls and columns that have surfaces exposed to temperatures below 32°F (0°C) in service.

3. **Partial load, exposed**: Elements that will carry loads that are less than the available early-age load capability of the structural member and that will have the opportunity to cure additionally before carrying service loads and that will be exposed to freezing and thawing in service (Line 3 of Table 7.2).

4. **Full load**: Elements that require reshoring to withstand construction loads before they are fully cured (Line 4 of Table 7.2 and Chapter 8). This would include plain or reinforced structural concrete.

7.5—Temperature drop after removal of protection

At the end of the protection period, protection removal should result in gradual cooling of concrete surfaces not exceeding the rates indicated in Table 5.1. This can be accomplished by slowly eliminating sources of heat, or leaving insulation in place until the concrete has essentially reached equilibrium with the mean ambient temperatures. Insulated forms, however, can present some difficulties in lowering the surface temperatures. Initial loosening of forms away from the concrete and covering with polyethylene sheets to allow some air circulation can alleviate the problem. As shown in Table 5.1, the maximum allowable cooling rates for surfaces of mass concrete are lower than...
for thinner members because mass concrete develops higher thermal gradients and, thus, is more susceptible to thermally induced cracking.

7.6—Allowable temperature differential during stripping

Although concrete should be cooled to ambient temperatures to avoid thermal cracking, a temperature differential may be permitted when protection is discontinued. For example, use Fig. 7.6 to determine the maximum allowable difference between the concrete temperature in a wall and the ambient air temperature with winds not exceeding 15 mph (24 km/h). These curves compensate for the wall thickness and its shape restraint factor, which is governed by the ratio of wall length to wall height. Modeling, as described in Chapter 8, can be used to estimate differential temperatures.

CHAPTER 8—PROTECTION AGAINST FREEZING FOR STRUCTURAL CONCRETE REQUIRING CONSTRUCTION SUPPORTS

8.2—Field-cured cylinders

Field-cured cylinders intended to be cured with the structure were once widely accepted to represent the lowest likely strength of the concrete. Field-cured cylinders can cause confusion and unnecessary delay in construction. The use of field-cured cylinders is inappropriate and should not be allowed in cold weather concreting. This is mainly related to the difficulty in maintaining the cylinders in any approximation of the condition of the structure. In-place testing, maturity testing, or both, should be used instead.

8.3—In-place testing

A number of techniques are available for estimating the in-place strength of concrete (ACI 228.1R). When these have been correlated to standard-cured cylinders, they can be used to determine the concrete strength. Tests are performed using simple handheld equipment. Pullout strength testing (ASTM C900) requires placing bolts in the concrete before casting. Individual bolts are then pulled out of the structure. Penetration resistance (ASTM C803/803M) is a technique that involves driving metal probes or pins in the concrete using a powder-actuated tool. Pulse velocity measurements (ASTM C597) are also used to estimate concrete strength.

8.4—Maturity testing

Concrete maturity is based on the concept that the combination of curing time and temperature of the concrete yields a specific strength for a given concrete mixture. There are a number of ASTM test methods that deal with maturity testing (ASTM C918/C918; ASTM C1074). The maturity concept as originally defined by Saul (1951) considers the relationship of time, temperature, and strength gain. The
equivalent age concept (Hansen and Pedersen 1977), based on principles of chemical kinetics, applies a nonlinear reaction response that is shown to be accurate in estimating in-place concrete strength under varying concrete curing temperatures. An understanding of heat flow and the identification of measurement points is of critical importance. Temperature should be measured at locations determined and specified by the licensed design professional. The maturity method develops a relationship between time-temperature history and concrete compressive strength. As detailed in ASTM C1074, it is required that a maturity relationship be developed for each specific concrete mixture. Changes in the mixture proportioning, such as using different amounts of cementitious material, admixtures, and changing the w/cm will affect the maturity relationship.

The principle of the maturity method is that the strength of a given concrete mixture can be related to the concrete temperature and time. To use this technique, establish a strength-versus-maturity index curve by performing compressive strength tests at various ages on cylinders made with concrete similar to that which will be used in construction. Usually, specimens are cured at room temperature and the temperature history of the concrete is recorded to compute the maturity factor at the time of testing. Average cylinder strengths and corresponding maturity indexes at each test age are plotted, and a smooth curve is fitted to the data.

To predict the in-place strength of properly cured concrete at a particular location and at a particular time, determine the maturity index at that time and read the corresponding strength on the strength-maturity relationship curve. The in-place maturity index at a particular location is determined by measuring the temperature of the concrete at close time intervals and using Eq. (8.4) to sum the successive products of the time intervals and the corresponding average concrete temperature above the datum temperature.

\[ M = \sum (T - T_d) \Delta t \]  

(8.4)

where \( M \) is temperature time factor (maturity index), deg-h; \( T \) is temperature of concrete, °F (°C); \( T_d \) is datum temperature, °F (°C); and \( \Delta t \) is duration of curing period at temperature \( T \), h.

Temperatures can be measured with expendable thermistors or thermocouples cast in the concrete. Embed the temperature sensors in the structure at critical locations in terms of severity of exposure and loading conditions. Electronic instruments known as maturity meters permit direct and continuous determination of the maturity index at a particular location in the structure. Maturity meters use a probe inserted into a tube embedded in the concrete or probes embedded directly into the concrete to measure the temperature, as shown in Fig. 8.4. They automatically compute and display the maturity index in degree-hours.

Strength prediction based on the maturity index assumes the in-place concrete has the same strength potential as the concrete used to develop the strength-maturity relationship. Before removing forms, soffits, or shores, it is necessary to determine whether the in-place concrete has attained the target strength by validating the strength determined from the strength-maturity relationship by performing additional tests such as:

(a) Early-age strength comparison in accordance with ASTM C918/C918

(b) Early-age strength test of standard-cured cylinders fitted with maturity data loggers (ASTM C1074)
   i. Determine the compressive strength of the test cylinders in accordance with ASTM C39/C39M.
   ii. Compare the compressive strength of the cylinders with the established strength-maturity relationship.
   iii. If these differ by more than 10 percent, a new strength-maturity relationship is needed, and another test is needed to determine the in-place strength of the concrete.
(c) Cylinders cast in-place in cylindrical molds in accordance with ASTM C873/C873M
(d) Penetration resistance test in accordance with ASTM C803/803M
(e) Pullout test in accordance with ASTM C900

If the strength-maturity relationship does not correlate with the strength obtained from a validation test, perform additional testing to ensure the in-place strength is adequate before removing forms, soffits, or shores.

**8.4.1 Example illustrating the maturity method**—In anticipation of cold weather, a contractor installed temperature sensors at critical locations in a concrete wall placed at 9 a.m. on Sept. 1. A history of the strength gain for the particular concrete mixture to be used in the wall had been developed under laboratory conditions, and the strength-maturity relationship (Fig. 8.4.1) was established. A record of the in-place concrete temperature was maintained as indicated in Columns 2 and 3 of Table 8.4.1. After 3 days (72 hours), the contractor needed the in-place strength of the concrete in the wall. Using the temperature record, the contractor calculated the average temperature (Column 4) during the various time intervals. The temperature is adjusted (Column 5) by subtracting the datum temperature \( T_d \) of 23°F (−5°C) from the average temperature (Column 4). The degree-hour, \( (T - T_d) \Delta t \), is calculated in Column 7, and the maturity index is calculated at different ages (Column 8). Based on
### Table 8.4.1—Calculation of maturity index and estimated in-place strength

<table>
<thead>
<tr>
<th>Date</th>
<th>Elapsed time in structure</th>
<th>Temperature in structure, °F</th>
<th>Average temperature in structure, °F</th>
<th>Column 4 – T₀°</th>
<th>Time interval, Δt, h</th>
<th>Maturity index M</th>
<th>Corresponding compressive strength, psi</th>
<th>Compressive strength, percent of 28-day moist-cured concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>09/01</td>
<td>0</td>
<td>50</td>
<td>10</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>1600</td>
<td>1100</td>
</tr>
<tr>
<td></td>
<td>12</td>
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<td>10</td>
<td>27</td>
<td>15</td>
<td>320</td>
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<td>24</td>
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<td>400</td>
</tr>
<tr>
<td>09/03</td>
<td>48</td>
<td>48</td>
<td>9</td>
<td>24</td>
<td>13</td>
<td>430</td>
<td>230</td>
<td>1220</td>
</tr>
<tr>
<td></td>
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<td>1510</td>
</tr>
<tr>
<td>09/04</td>
<td>72</td>
<td>44</td>
<td>7</td>
<td>22</td>
<td>12</td>
<td>260</td>
<td>140</td>
<td>1770</td>
</tr>
<tr>
<td>09/08</td>
<td>168</td>
<td>42</td>
<td>6</td>
<td>20</td>
<td>11</td>
<td>1920</td>
<td>1060</td>
<td>3690</td>
</tr>
<tr>
<td>09/11</td>
<td>240</td>
<td>42</td>
<td>6</td>
<td>19</td>
<td>11</td>
<td>1370</td>
<td>790</td>
<td>5060</td>
</tr>
<tr>
<td>09/14</td>
<td>312</td>
<td>42</td>
<td>6</td>
<td>19</td>
<td>11</td>
<td>1370</td>
<td>490</td>
<td>6430</td>
</tr>
</tbody>
</table>

*The datum temperature T₀ is 23°F (-5°C).*

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**Fig. 8.4.1—Example of a strength-maturity factor relationship for laboratory-cured cylinders (73°F [22.8°C]).**

The strength-maturity relationship (Fig. 8.4.1), the predicted in-place strength (Column 9) at 72 hours is 1600 psi (11.0 MPa). By continuing the procedure, strength at later ages can be predicted.

**8.5—Attainment of design strength**

In general, strength gain is dependent on the curing environment of the work, including temperature and moisture conditions. Figure 8.5 illustrates the strength development of concrete specimens removed from moist curing at various ages and subsequently exposed to laboratory air. As the specimens dried, strength gain ceased. For this reason, the curing and protection conditions should be maintained to ensure adequate early-age strength gains to meet the specified required strength prior to terminating cold weather protection of temporarily supported structures.

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**Fig. 8.5—Compressive strength of concrete dried in laboratory air after preliminary moist curing (Price 1951).**

**8.6—Increasing early strength**

Many factors influence the time needed for concrete to attain the strength specified for safe removal of formwork. Most important are those that affect the rate and level of strength development, including:

(a) Initial temperature of the concrete when placed
(b) Temperature at which the concrete is maintained
(c) Type, amount, and properties of the cementitious materials
(d) w/cm
(e) Type and dose of accelerating and other admixtures used

(f) Conditions of protection and curing

Economic considerations may dictate an accelerated construction schedule even though the resulting concrete may be of lesser quality in terms of reduced long-term ultimate strength or increased thermal cracking. In such cases, the early-age strength of the concrete may be increased and the duration of protection may be substantially reduced by:

(a) Increasing the temperature during protection to a level higher than indicated in Line 1 of Table 5.1. Figure 8.6 illustrates the effects of curing temperature on strength development, where strength is expressed as a percentage of the strength at the same age for curing at 73°F (23°C). Note that Type I and III cements provide higher strengths than Type II at early ages. Because of variations in the performance of any given cement, use the data in Fig. 8.6 only as a guide

(b) Using types and compositions of cement that exhibit higher early-age strength development and using higher cement content with a lower w/cm (11:1)

(c) Using an accelerating admixture conforming to ASTM C494/C494M, Type C (accelerating), or Type E (water-reducing and accelerating). Refer to Chapter 11 for further information on using calcium chloride (CaCl₂) or Type C or Type E admixtures containing CaCl₂

(d) Reducing the w/cm to increase the 28-day strength, thus increasing the early-age strength

(e) Increase the volume of cement used in the mixture

(f) Increase the use of various supplementary cementitious materials to increase early-age strength development

Due to variation in performance with different cement brands and types, perform tests in advance at the anticipated curing temperature using the cement, aggregates, and admixtures proposed for use. Additionally, it is important to consider the long-term affects that these acceleration and heating processes can have on the concrete, including cracking due to thermal stresses, autogenous shrinkage cracking, issues relating to self-desiccation, and other problems.

8.7—Cooling concrete

To lower the likelihood of cracking due to thermal stresses, take precautions to assure gradual cooling of concrete surfaces at the termination of the protection period. Refer to Line 5 of Table 5.1 for recommended temperature gradients.

8.8—Estimating strength development

When adequate curing and protection is provided but no actions are taken to determine the level of strength development, conservative estimates of concrete strength are recommended. In such cases, use Table 8.8 as a conservative guide to determine the recommended duration of curing and protection at 50 or 70°F (10 or 21°C) to achieve different percentages of the standard-cured 28-day strength.

8.9—Removal of forms and supports

The removal of forms and supports and the placement and removal of reshores should be in accordance with the recommendations of ACI 347.2R and ACI 347R:

(a) The in-place strength of concrete required to permit removal of forms and shores should be specified by the licensed design professional

(b) Perform nondestructive tests of in-place concrete (8.3 and 8.4)

(c) Nondestructive testing should be correlated with the actual concrete mixture used

(d) Methods to evaluate the concrete strength tests results should be completely prescribed in the specifications

(e) A record of all tests, as well as records of weather conditions and other pertinent information, should be used by the architect/engineer in deciding when to permit removal of forms and shores

(f) The reshoring procedure, which can be affected by cold weather, is one of the most critical operations in formwork that should be planned in advance and reviewed by the licensed design professional.

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Fig. 8.6—Effect of temperature conditions on the strength development of concrete (Type I cement) (Klieger 1958) (Note: \(T_c = (T_f - 32°F)/1.8\)).

Table 8.8—Duration of recommended protection for percentage of standard-cured 28-day strength

<table>
<thead>
<tr>
<th>Percentage of standard-cured 28-day strength</th>
<th>At 50°F (10°C), days</th>
<th>At 70°F (21°C), days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of cement</td>
<td>I</td>
<td>II</td>
</tr>
<tr>
<td>Type of cement</td>
<td>50</td>
<td>6</td>
</tr>
<tr>
<td>Type of cement</td>
<td>65</td>
<td>11</td>
</tr>
<tr>
<td>Type of cement</td>
<td>85</td>
<td>21</td>
</tr>
<tr>
<td>Type of cement</td>
<td>95</td>
<td>29</td>
</tr>
</tbody>
</table>

*The data in this table were derived from concretes with strengths from 3000 to 5000 psi (20.7 to 34.4 MPa) after 28 days of curing at 70 ± 3°F (21 ± 1.7°C), and did not contain fly ash. The 28-day strength for each type of cement was considered as 100 percent in determining the times to reach various percentages of this strength for curing at 50 and 70°F (10 and 21°C). These times are only approximate, and specific values should be obtained for the concrete used on the job.
8.10—Estimating strength development: modeling cold weather placements

The proposed protection scheme can be modeled to predict concrete temperature-time properties.

Numerous commercial and proprietary computer programs have been developed that generally employ the finite element or finite difference models changing boundary and initial conditions. These are useful to predict not only temperature but, combined with the maturity concept, to predict the strength of the concrete at later ages.

Two assumptions commonly used during modeling are:

1. Early-age concrete hydration is negligible below a concrete temperature of 40°F (5°C).
2. Freezing damage may take place when the concrete temperature drops below 32°F (0°C).

These assumptions are conservative. The liquidus point of the concrete pore water is depressed from the effects of soluble materials contained in the pore water. As a result, some strength gain will occur below 40°F (5°C).

Additional data, such as the strength gain of the particular concrete under study at low temperatures and the thermodynamic properties of the concrete in question at early ages, could be determined for more accurate modeling of individual placements.

Thermal modeling is used to predict the need for insulation or external heating and to schedule stripping, stressing, or other strength-sensitive activities.

CHAPTER 9—EQUIPMENT, MATERIALS, AND METHODS OF TEMPERATURE PROTECTION

9.1—Introduction

The temperature of concrete placed during cold weather should be maintained at the recommended temperature given in Line 1 of Table 5.1, and for the length of time recommended in Table 7.2, or until the in-place strength has reached the level specified by the licensed design professional to terminate protection. The specific protection system needed to maintain the recommended temperatures depends on factors such as ambient weather conditions, geometry of the structure, and concrete mixture proportions. In some instances, when ambient weather conditions are relatively mild, it may only be necessary to cover the concrete with insulating materials and use the natural heat of hydration to maintain the recommended temperature levels. However, when ambient temperatures are low or winds are high, or both, it may be necessary to build enclosures and use heaters to maintain the recommended temperatures. In many instances, hydronic heaters and insulation blankets are adequate to maintain concrete placements within the proper curing temperature range.

9.2—Insulating materials

Because most of the cement’s heat of hydration is generated during the first 3 days, external heating sources may not be needed to prevent concrete freezing and to maintain strength development temperatures where the generated heat is retained. Heat of hydration is retained by using insulating blankets on unformed surfaces and by using insulating forms (Tuthill et al. 1951; Wallace 1954; Mustard and Ghosh 1979). To be effective, keep insulation in close contact with the concrete or the form surface. Some commonly used insulating materials include:

- (a) Polystyrene foam sheets: Sheets can be cut to shape and wedged between the studs of the forms or glued into place.
- (b) Urethane foam: Foam may be sprayed onto the surface of forms, making a continuous insulating layer. Good weather-resistant enamel should be sprayed over urethane foam to reduce water absorption and protect it from ultraviolet rays. Use urethane foam with caution because it generates highly noxious fumes when exposed to fire.
- (c) Insulation blankets: Blankets should be fully moisture-impermeable so moisture does not lessen insulating effectiveness. Outer shells are typically made of woven reinforced polyethylene or laminated polyethylene. The inner thermal insulating layers are typically made of closed-cell polypropylene foam, closed-cell polyethylene foam, or air-filled pockets. Some higher-performing blankets incorporate a reflective metal foil layer to reflect emitted radiant energy back to the insulated surface. Blankets containing mineral wool, fiberglass, cellulose fibers, or open-cell foam materials are not recommended because they do not perform well when wet.
- (d) Straw: Straw is not recommended because it is bulky, highly flammable, ineffective when wet, can cause staining and impressions in the surface, and difficult to keep in place, especially during windy conditions.
- (e) Polyethylene sheeting: Polyethylene sheeting is a suitable moisture barrier for keeping moisture for hydration in the concrete. Often, polyethylene sheeting is used with insulation blankets, heaters, or both, to provide moisture retention and prevent carbonation. Although polyethylene sheeting has a low thermal resistance (R-value), the sheeting alone can greatly reduce concrete heat loss on cold, windy days. Sheet ing prevents moisture evaporation, which is a significant cooling process, especially with high winds. Usually, polyethylene can be placed earlier on the slab than can insulation blankets, so moisture retention and cold-weather protection can begin sooner.

9.3—Selection of insulation when supplementary heat is not used

Concrete temperature records reveal the effectiveness of different amounts or types of insulation and of other protection methods for various types of concrete work under different weather conditions. Using these temperature records, appropriate modifications can be made to the protection method or selected materials. Various methods for estimating temperatures maintained by various insulation arrangements under given weather conditions have been published (Tuthill et al. 1951; Mustard and Ghosh 1979).

As mentioned in 9.2, the heat of hydration is high during the first 3 days after placement and then gradually decreases. To maintain a specified temperature throughout the protection period, the amount of recommended insulation is greater for a long protection period than for a shorter one. Conversely,
Table 9.3a—Minimum exposure temperatures for concrete slabs above ground and walls for concrete placed and surface temperature maintained for 50°F (10°C) for 7 days (Timms and Withey 1934)

<table>
<thead>
<tr>
<th>Wall or slab thickness, in. (m)</th>
<th>Minimum ambient air temperature, °F (°C), allowable when insulation having these values of thermal resistance ( R ), h ft²·°F/BTU (m²·K/W), is used</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( R = 2 ) (0.35)</td>
</tr>
<tr>
<td></td>
<td>Cement content = 300 lb/yd³ (178 kg/m³)</td>
</tr>
<tr>
<td>6 (0.15)</td>
<td>48 (9)</td>
</tr>
<tr>
<td>12 (0.30)</td>
<td>45 (7)</td>
</tr>
<tr>
<td>18 (0.46)</td>
<td>41 (5)</td>
</tr>
<tr>
<td>24 (0.61)</td>
<td>38 (3)</td>
</tr>
<tr>
<td>36 (0.91)</td>
<td>32 (0)</td>
</tr>
<tr>
<td>48 (1.20)</td>
<td>26 (-3)</td>
</tr>
<tr>
<td>60 (1.50)</td>
<td>26 (-3)</td>
</tr>
<tr>
<td></td>
<td>Cement content = 400 lb/yd³ (237 kg/m³)</td>
</tr>
<tr>
<td>6 (0.15)</td>
<td>47 (8)</td>
</tr>
<tr>
<td>12 (0.30)</td>
<td>43 (6)</td>
</tr>
<tr>
<td>18 (0.46)</td>
<td>39 (4)</td>
</tr>
<tr>
<td>24 (0.61)</td>
<td>34 (1)</td>
</tr>
<tr>
<td>36 (0.91)</td>
<td>25 (-4)</td>
</tr>
<tr>
<td>48 (1.20)</td>
<td>18 (-8)</td>
</tr>
<tr>
<td>60 (1.50)</td>
<td>18 (-8)</td>
</tr>
<tr>
<td></td>
<td>Cement content = 500 lb/yd³ (296 kg/m³)</td>
</tr>
<tr>
<td>6 (0.15)</td>
<td>47 (8)</td>
</tr>
<tr>
<td>12 (0.30)</td>
<td>42 (6)</td>
</tr>
<tr>
<td>18 (0.46)</td>
<td>36 (2)</td>
</tr>
<tr>
<td>24 (0.61)</td>
<td>30 (-1)</td>
</tr>
<tr>
<td>36 (0.91)</td>
<td>18 (-8)</td>
</tr>
<tr>
<td>48 (1.20)</td>
<td>10 (-12)</td>
</tr>
<tr>
<td>60 (1.50)</td>
<td>10 (-12)</td>
</tr>
<tr>
<td></td>
<td>Cement content = 600 lb/yd³ (356 kg/m³)</td>
</tr>
<tr>
<td>6 (0.15)</td>
<td>46 (8)</td>
</tr>
<tr>
<td>12 (0.30)</td>
<td>40 (4)</td>
</tr>
<tr>
<td>18 (0.46)</td>
<td>33 (1)</td>
</tr>
<tr>
<td>24 (0.61)</td>
<td>26 (-3)</td>
</tr>
<tr>
<td>36 (0.91)</td>
<td>12 (-11)</td>
</tr>
<tr>
<td>48 (1.20)</td>
<td>4 (-16)</td>
</tr>
<tr>
<td>60 (1.50)</td>
<td>4 (-16)</td>
</tr>
</tbody>
</table>

* < -60°F (-51°C).

for a given insulation system, concrete protected for a short period, such as 3 days, can be exposed to a lower ambient temperature than concrete protected for 7 days.

Tables 9.3a, 9.3b, 9.3c, and 9.3d indicate the minimum ambient air temperatures to which concrete walls or slabs of different thicknesses may be exposed for different values of thermal resistance \( R \), for different cement contents, and for protection periods of 3 or 7 days. For protection periods shorter than 3 days, use the tables or figures for 3 days. For these figures and tables, the concrete temperature as placed is assumed to be 50°F (10°C).

Use these tables and figures to determine the recommended thermal resistance \( R \) under different conditions. \( R \)-values are often cited without units; however, the U.S.
Table 9.3c—Minimum exposure temperatures for concrete flatwork placed on ground for concrete placed and surface temperature maintained at 50°F (10°C) for 7 days on ground at 35°F (2°C) (Timms and Withey 1934)

<table>
<thead>
<tr>
<th>Slab thickness, in. (m)</th>
<th>Minimum ambient air temperature, °F (°C), allowable when insulation having these values of thermal resistance $R$, h·f·ft²·°F/BTU (m²·K/W), is used</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 (0.10)</td>
<td>* * *</td>
</tr>
<tr>
<td>8 (0.20)</td>
<td>* * *</td>
</tr>
<tr>
<td>12 (0.31)</td>
<td>* * *</td>
</tr>
<tr>
<td>18 (0.46)</td>
<td>46 (8) 42 (6) 36 (2) 30 (-1)</td>
</tr>
<tr>
<td>24 (0.61)</td>
<td>40 (4) 31 (1) 22 (6) 11 (-12)</td>
</tr>
<tr>
<td>30 (0.76)</td>
<td>35 (2) 22 (6) 7 (-14) -8 (-22)</td>
</tr>
<tr>
<td>36 (0.91)</td>
<td>31 (1) 13 (-11) -5 (-21) -23 (-31)</td>
</tr>
</tbody>
</table>

Cement content = 300 lb/yd³ (178 kg/m³)

<table>
<thead>
<tr>
<th>Slab thickness, in. (m)</th>
<th>Minimum ambient air temperature, °F (°C), allowable when insulation having these values of thermal resistance $R$, h·f·ft²·°F/BTU (m²·K/W), is used</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 (0.10)</td>
<td>* * *</td>
</tr>
<tr>
<td>8 (0.20)</td>
<td>* * *</td>
</tr>
<tr>
<td>12 (0.31)</td>
<td>* * *</td>
</tr>
<tr>
<td>18 (0.46)</td>
<td>41 (5) 32 (0) 22 (-6) 12 (-11)</td>
</tr>
<tr>
<td>24 (0.61)</td>
<td>35 (2) 19 (-7) -1 (-17) -15 (-26)</td>
</tr>
<tr>
<td>30 (0.76)</td>
<td>28 (-2) 8 (-13) -14 (-26) -36 (-38)</td>
</tr>
<tr>
<td>36 (0.91)</td>
<td>23 (-5) -4 (-20) -29 (-34) -54 (-48)</td>
</tr>
</tbody>
</table>

Cement content = 400 lb/yd³ (237 kg/m³)

<table>
<thead>
<tr>
<th>Slab thickness, in. (m)</th>
<th>Minimum ambient air temperature, °F (°C), allowable when insulation having these values of thermal resistance $R$, h·f·ft²·°F/BTU (m²·K/W), is used</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 (0.10)</td>
<td>* * *</td>
</tr>
<tr>
<td>8 (0.20)</td>
<td>* * *</td>
</tr>
<tr>
<td>12 (0.31)</td>
<td>* * *</td>
</tr>
<tr>
<td>18 (0.46)</td>
<td>48 (9) 47 (7) 40 (4) 36 (2)</td>
</tr>
<tr>
<td>24 (0.61)</td>
<td>36 (2) 22 (-6) 14 (-13) -6 (-21)</td>
</tr>
<tr>
<td>30 (0.76)</td>
<td>28 (-2) 16 (-14) -16 (-27) -38 (-39)</td>
</tr>
<tr>
<td>36 (0.91)</td>
<td>23 (-5) -18 (-28) -50 (-46)</td>
</tr>
</tbody>
</table>

Cement content = 500 lb/yd³ (296 kg/m³)

<table>
<thead>
<tr>
<th>Slab thickness, in. (m)</th>
<th>Minimum ambient air temperature, °F (°C), allowable when insulation having these values of thermal resistance $R$, h·f·ft²·°F/BTU (m²·K/W), is used</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 (0.10)</td>
<td>* * *</td>
</tr>
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<td>8 (0.20)</td>
<td>* * *</td>
</tr>
<tr>
<td>12 (0.31)</td>
<td>* * *</td>
</tr>
<tr>
<td>18 (0.46)</td>
<td>44 (7) 38 (3) 32 (0) 26 (-3)</td>
</tr>
<tr>
<td>24 (0.61)</td>
<td>31 (-1) 14 (-10) -5 (-21) -24 (-31)</td>
</tr>
<tr>
<td>30 (0.76)</td>
<td>22 (-6) -5 (-21) -32 (-36) -61 (-52)</td>
</tr>
<tr>
<td>36 (0.91)</td>
<td>14 (-10) -19 (-28) -67 (-55)</td>
</tr>
</tbody>
</table>

Cement content = 600 lb/yd³ (356 kg/m³)

$> 50°F (10°C)$: additional heat required.
$\pm -60°F (-51°C)$.

Table 9.3d—Minimum exposure temperatures for concrete flatwork placed on ground for concrete placed and surface temperature maintained at 50°F (10°C) for 3 days on ground at 35°F (2°C) (Timms and Withey 1934)

<table>
<thead>
<tr>
<th>Slab thickness, in. (m)</th>
<th>Minimum ambient air temperature, °F (°C), allowable when insulation having these values of thermal resistance $R$, h·f·ft²·°F/BTU (m²·K/W), is used</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 (0.10)</td>
<td>* * *</td>
</tr>
<tr>
<td>8 (0.20)</td>
<td>* * *</td>
</tr>
<tr>
<td>12 (0.31)</td>
<td>* * *</td>
</tr>
<tr>
<td>18 (0.46)</td>
<td>42 (6) 38 (3) 32 (0) 26 (-3)</td>
</tr>
<tr>
<td>24 (0.61)</td>
<td>37 (3) 25 (-4) 11 (-12) -3 (-19)</td>
</tr>
<tr>
<td>30 (0.76)</td>
<td>31 (-1) 15 (-9) -1 (-18) -17 (-27)</td>
</tr>
<tr>
<td>36 (0.91)</td>
<td>31 (-1) 12 (-11) -5 (-21) -22 (-30)</td>
</tr>
</tbody>
</table>

Cement content = 300 lb/yd³ (178 kg/m³)

<table>
<thead>
<tr>
<th>Slab thickness, in. (m)</th>
<th>Minimum ambient air temperature, °F (°C), allowable when insulation having these values of thermal resistance $R$, h·f·ft²·°F/BTU (m²·K/W), is used</th>
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<tbody>
<tr>
<td>4 (0.10)</td>
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<tr>
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</tr>
<tr>
<td>18 (0.46)</td>
<td>46 (8) 44 (7) 42 (6) 38 (3)</td>
</tr>
<tr>
<td>24 (0.61)</td>
<td>36 (2) 22 (-6) 8 (-13) -21 (-29)</td>
</tr>
<tr>
<td>30 (0.76)</td>
<td>21 (-6) 0 (-18) -21 (-29) -42 (-41)</td>
</tr>
<tr>
<td>36 (0.91)</td>
<td>21 (-6) -4 (-20) -29 (-34) -50 (-46)</td>
</tr>
</tbody>
</table>

Cement content = 400 lb/yd³ (237 kg/m³)

<table>
<thead>
<tr>
<th>Slab thickness, in. (m)</th>
<th>Minimum ambient air temperature, °F (°C), allowable when insulation having these values of thermal resistance $R$, h·f·ft²·°F/BTU (m²·K/W), is used</th>
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<tr>
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</tr>
<tr>
<td>12 (0.31)</td>
<td>* * *</td>
</tr>
<tr>
<td>18 (0.46)</td>
<td>42 (6) 40 (4) 36 (2) 30 (-1)</td>
</tr>
<tr>
<td>24 (0.61)</td>
<td>36 (2) 22 (-6) 8 (-13) -21 (-29)</td>
</tr>
<tr>
<td>30 (0.76)</td>
<td>21 (-6) 0 (-18) -21 (-29) -42 (-41)</td>
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<td>36 (0.91)</td>
<td>21 (-6) -4 (-20) -29 (-34) -50 (-46)</td>
</tr>
</tbody>
</table>

Cement content = 500 lb/yd³ (296 kg/m³)

<table>
<thead>
<tr>
<th>Slab thickness, in. (m)</th>
<th>Minimum ambient air temperature, °F (°C), allowable when insulation having these values of thermal resistance $R$, h·f·ft²·°F/BTU (m²·K/W), is used</th>
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<tbody>
<tr>
<td>4 (0.10)</td>
<td>* * *</td>
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<tr>
<td>8 (0.20)</td>
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<tr>
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<td>* * *</td>
</tr>
<tr>
<td>18 (0.46)</td>
<td>42 (6) 36 (2) 30 (-1) 24 (-4)</td>
</tr>
<tr>
<td>24 (0.61)</td>
<td>36 (2) 22 (-6) 8 (-13) -21 (-21)</td>
</tr>
<tr>
<td>30 (0.76)</td>
<td>21 (-6) 0 (-18) -24 (-31) -48 (-44)</td>
</tr>
<tr>
<td>36 (0.91)</td>
<td>21 (-6) -4 (-20) -29 (-34) -50 (-46)</td>
</tr>
</tbody>
</table>

Cement content = 600 lb/yd³ (356 kg/m³)

$> 50°F (10°C)$: additional heat required.
$\pm -60°F (-51°C)$.

$>< -60°F (-51°C)$.

Customary units are (R·f·h)/BTU, and the SI units are (m²·K)/W. In this guide, U.S. customary units will be listed first with SI in parentheses. Use the insulation values (R-values) for the chosen insulating material based on manufacturer product data to obtain the recommended thermal resistance. The thermal resistance of various insulating materials has been calculated under the assumption that the insulation is applied to the exterior surfaces of steel forms. When 3/4 in. (20 mm) plywood forms are used, add an R-value of 0.94 (0.17) for the plywood form to the R-value of the insulation. The values shown in Fig. 9.3a to 9.3d are based on the assumption that wind speeds are not greater than 15 mph (24
km/h). With higher wind speeds, the effectiveness of a given thickness of insulation diminishes. However, at a wind speed of 30 mph (48 km/h), the decrease in the effective thermal resistance amounts to an R-value less than 0.1. For all practical purposes, the effects of wind speed may be neglected in determining the recommended thickness of added insulation.

Fig. 9.3b — Minimum exposure temperatures for concrete slabs above ground and walls as a function of member thickness, R-value, and cement content. Concrete placed and surface temperature maintained at 50°F (10°C) for 3 days (Timms and Withey 1934).

Corners and edges are particularly vulnerable during cold weather. The thickness of insulation for these parts should be approximately three times the thickness recommended for walls or slabs. In addition, the tables and figures are for cement having a heat of hydration similar to Type I portland cement. For Type II cement and blended hydraulic cements with moderate heat of hydration, increase the insulation recommendations given in the tables and figures by approximately 30 percent. Where other types of cements or blends of cement and other cementitious materials are used, similar proportional adjustments should be made to the amount of insulation (Tuthill et al. 1951; Mustard and Ghosh 1979).
Typical heat-of-hydration curves for various cements can be found in *PCA Bulletin No. IS128*. Do not use insulation beyond the recommended amount because it could raise the internal temperature of the concrete above recommended levels, which lengthens the gradual cooling period, increases thermal shrinkage, and increases the risk of cracking due to thermal shock.

### 9.3.1 Example

How to determine the recommended *R*-value of insulation:

**Problem**: A contractor anticipates placing an 18 in. (0.46 m) thick concrete wall when the ambient temperature will be 0°F (−18°C). The concrete will have a cement content of 500 lb/yd³ (296 kg/m³). There are no early-age strength requirements specified, and the wall will have no service or...
protected concrete surface or to the nonworking side of the heater. Direct fired heaters typically burn fuel oil, kerosene, propane, gasoline, or natural gas. Combustion of these fossil fuels produces a large amount of carbon dioxide (CO2) and, to a lesser extent, carbon monoxide (CO). Direct fired heaters discharge these products into the enclosed air space being heated; unless the concrete is protected from these gases, they are not suitable for cold weather concreting applications. Carbon dioxide combines with calcium hydroxide (Ca(OH)2) on the surface of freshly placed concrete to form calcium carbonate (CaCO3) (Kauer and Freeman 1955). This CaCO3 layer interferes with the hydration reaction and results in a soft, chalky surface that continues to dust for the life of the concrete. Carbon monoxide produced by direct fired heaters can build up in the workspace and present a hazard to workers. Direct fired heaters should be vented and not used to directly heat the surface of the concrete.

9.5.3 Indirect fired heaters—Indirect fired heaters are similar to direct fired heaters in many respects. They are approximately the same size, typically burn the same fossil fuels, produce the same products of combustion, and have a fan to help circulate the hot air. Indirect fired heaters differ from direct fired heaters in one important respect. Because the exhaust in an indirect fired heater is separate from the hot air and is vented outdoors, only clean air discharges into the enclosed workspace. Indirect fired hot air heaters are suitable for heating enclosures when placing concrete in cold weather.

9.5.4 Hydronic heating systems—Hydronic heaters typically burn diesel fuel or kerosene to heat a propylene glycol/water heat transfer fluid. The heater remains outdoors so no products of combustion enter the workspace or contact the concrete. The heat-transfer fluid circulates through a system of heat-transfer hoses. After the concrete placement reaches its final set, cover it with 4 to 6 mil polyethylene film or other suitable material to serve as a vapor barrier. Place the heat-transfer hoses on top of the vapor barrier and cover with insulating materials as recommended in 9.2. Use enough insulation to prevent heat loss. Hydronic heaters can be used outdoors to thaw or preheat subgrades before concrete placement. They are also used to provide supplementary heat to curing formed walls, columns, elevated slabs, slabs-on-ground, foundations, and tilt-up wall panels. Construction of temporary enclosures is generally unnecessary. Hydronic heaters can be used on areas much larger than could be temporarily enclosed. Where an enclosure is built for other reasons, such as to serve as a wind barrier or to protect against heavy snowfall, or if an area is inside an enclosed building, a hydronic heater can provide economical heat. The insulation blankets confine delivered heat to the surface to be heated instead of heating the entire air space in the enclosure or building. Hydronic heating systems can be connected to liquid-to-air heat exchangers to produce flame-free hot air if a particular project demands hot air. Hydronic heaters provide an even distribution of heat such that curling and cracking induced by temperature gradients within concrete are almost eliminated (Grochoski 2000).

9.6—Enclosures

Although enclosures can be the most effective means of protection, they can also be the most expensive. The need for enclosures depends on the nature of the structure and the weather conditions, such as wind and snow. Experience has shown that they are generally needed for placing operations when the air temperature is lower than -5°F (-20°C). Enclosures block the wind, keep out cold air, and conserve heat. They are made with materials such as wood, canvas, building board, or plastic sheeting. Enclosures made with flexible materials are less expensive and easier to build and remove. Enclosures built with rigid materials are more effective in blocking wind and maintaining perimeter temperatures. Enclosures should be capable of withstanding wind and snow loads and be reasonably airtight. Maintain and
repair enclosures to retain their performance. Provide sufficient space between the concrete and the enclosure to permit free circulation of the warmed air. Provide sufficient headroom so workers can work efficiently.

Heat can be supplied to enclosures by hydronic heaters, live steam, hot forced air, or indirect fired combustion heaters. Using hydronic heaters is economical because the heat is applied directly to the concrete instead of heating the entire air space within the enclosure.

Although live steam heating provides a favorable curing environment, it offers less-than-ideal working conditions and can cause icing problems around the perimeter of the enclosure. Forced hot air or indirect fired combustion heaters can also be used. Heaters and ducts should be positioned such that the hot, dry air does not cause areas of overheating or drying of the concrete surface. Apply a suitable vapor barrier as soon as practical after final set. During the protection period, concrete surfaces should not be exposed to air at more than 20°F (11°C) above the minimum placement temperatures given in Line 1 of Table 5.1, unless higher values are recommended by an accepted curing method.

9.7—Internal heating
Concrete can be heated internally or from below by embedding heat-transfer tubing similar to that used in in-floor heating systems. A hydronic heater is connected to supply the warm heat-transfer fluid. Prevent moisture loss due to evaporation from unformed surfaces by covering the surfaces with 4 to 6 mil polyethylene film. Place insulating materials in accordance with 9.2 and 9.4 to retard thermal losses. Monitor concrete temperatures so they are not significantly below or above recommended values.

Concrete can be heated internally by using embedded coiled and insulated electrical resistors. Low-voltage current passes through coils embedded near the section surface in a predetermined pattern. Raise internal concrete temperature to any recommended level by selecting the appropriate spacing or pitch of the coils. Control gradual cooling by intermittently interrupting the current passing through the coils. Heating usually begins after a presetting period of 4 to 5 hours, depending on the setting characteristics of the concrete. Address moisture retention and temperature control in the same manner as described above.

9.8—Temperature monitoring
To ensure concrete temperatures are maintained as recommended in Table 5.1, concrete placements should be embedded with expendable thermistors or thermocouples so actual temperatures are monitored over time and corrective actions can be taken to adjust concrete temperatures if they drift outside the recommended ranges. Electronic data loggers should be employed to automatically read the thermistors and record and store time and temperature readings. Thermistors or thermocouples should be strategically placed to monitor typical, as well as atypical, sections of the placement. Monitor temperatures near the surfaces, as well as in the central interior of sections. Historical temperature data can be used to predict developed strength. Refer to the maturity method in 8.4. Historical temperature data should be retained as a part of the construction project record of the structure.

9.9—Temporary removal of protection
Insulation blankets, housing, and enclosures should remain in place for the entire protection period. Sections may be temporarily removed to permit placing additional forms or concrete, but scheduling this work should ensure the previously placed concrete does not freeze. Sections removed should be replaced as soon as forms or concrete are in final position. The time while protection is temporarily removed is not considered part of the protection period and any time lost should be made up with twice the number of lost degree-hours before discontinuing protection. For example, if protection was temporarily removed for 6 hours and the surface temperature dropped 15°F (8.3°C) below the minimum value in Table 5.1, the deficiency in protection would be 90°F-hour (50°C-hour). Therefore, extend the protection period for 180°F-hour (100°C-hour).

9.10—Insulated forms
When using insulated forms in addition to heated enclosures, monitor the interior and surface temperature of the concrete to ensure the concrete is not heated more than necessary. This applies particularly to mass concrete. For further information on mass concrete, refer to ACI 207.4R.

CHAPTER 10—CURING RECOMMENDATIONS AND METHODS

10.1—Introduction
Newly placed concrete should be protected from surface desiccation so that hydration can continue to occur. Measures should be taken to inhibit evaporation of moisture from concrete. Freshly placed concrete is vulnerable to freezing when it is critically saturated. Therefore, concrete should be allowed to undergo some drying before being exposed to temperatures below 32°F (0°C).

10.2—Curing during the protection period inside an enclosure
Concrete exposed to cold weather is unlikely to dry at an undesirable rate, but this is not always true for concrete protected from cold weather. As long as forms remain in place, concrete surfaces adjacent to the forms will retain adequate moisture. Exposed horizontal surfaces, however—in particular, finished floors—are prone to rapid drying in a heated enclosure.

When concrete warmer than 60°F (16°C) is exposed to air 50°F (10°C) or higher, take measures to inhibit surface desiccation. The preferred technique is to use steam for heating and inhibiting evaporation because it introduces additional moisture to the surface along with additional heat. When dry heating is used, concrete should be covered with an approved impervious material or a curing compound meeting the requirements of ASTM C309, or water cured. Water curing is not recommended during periods when temperatures...
are below 32°F (0°C) due to potential surface freezing, unless additional protection measures are employed. It also increases the likelihood of the concrete exposure to freezing and thawing in a nearly saturated condition when protection is removed. Where water or steam curing are used, terminate the curing 12 hours before the end of the temperature protection period. Allow the concrete to dry naturally for 12 hours prior to and during the gradual adjustment to ambient conditions, as discussed in 7.5.

When the air temperature within the enclosure falls to 50°F (10°C), the concrete can be exposed to the air, provided the relative humidity is not less than 40 percent. If the relative humidity is less than 40 percent inside the enclosure, it is necessary to add moisture to the air to maintain at least 40 percent relative humidity, and inhibit desiccation of the exposed surface.

10.3—Curing following the protection period

Following removal of temperature protection, it is usually unnecessary to provide measures to prevent surface desiccation as long as the air temperature remains below 50°F (10°C), and the relative humidity is greater than 40 percent. Applying a curing compound during the first period where the ambient temperature rises above 32°F (0°C) after protection removal eliminates the need to conduct further curing operations when the temperature rises above 50°F (10°C). However, application of a curing compound may affect the bonding of future floor covering.

CHAPTER 11—ACCELERATION OF SETTING AND STRENGTH DEVELOPMENT

11.1—Introduction

Where proper precautions are taken, accelerating admixtures, Type III cement (high-early-strength), or additional cement can be used to shorten the time needed to accelerate time of set and strength development. Materials or methods used to obtain high-early-strength concrete increase the rate of heat development from hydration, which may be favorable in some instances. The reduction in time of set and acceleration of strength gain often result in savings due to shorter protection period, faster reuse of forms, earlier removal of shores, and reduction in finishing time.

Accelerated strength development of concrete in massive structures may not be beneficial in cold weather because high internal temperatures increase the potential for cracking due to thermal gradients. The development of thermal gradients in massive concrete structures should be investigated by referring to ACI 207.1R.

Cements of the same type, brand, and fineness can have wide variations in time of set and rates of strength development. To determine which alternative produces the desired acceleration, testing the concrete made with the cements to be used for a particular job is recommended. If additional cement is considered, trial batches using the increased cement content should be tested because the accelerated strength development varies with each cement and temperature exposure. The use of additional cement and the resulting increased water demand can increase shrinkage and curling of some structures, and should be evaluated by a licensed design professional. Although chemical admixtures are evaluated (ASTM C494/C494M) at 73°F (23°C), accelerating admixtures will frequently be more effective at lower concrete placement temperatures. If possible, test accelerating admixtures at the temperatures expected during concrete placement. Additional information on accelerating time of set and strength development is available in ACI 212.3R.

11.2—Accelerating admixtures

11.2.1 General—Accelerating admixtures are commonly used in cold weather concreting and are typically used in combination with other recommended cold weather concrete practices. Accelerators increase the rate of reaction between cement and water (hydration) at any given temperature. This effect can be used to offset the reduction in reaction rate due to lower temperatures. While reducing the time of set and increasing the rate of strength gain, these admixtures do not significantly lower the liquidus temperature of water in concrete. ACI 212.3R states accelerating admixtures lower the liquidus temperature of water in concrete by only 4°F (2°C).

Accelerating admixtures are classified into three primary categories:

1. Calcium chloride
2. Accelerating admixtures containing calcium chloride (CaCl₂)
3. Nonchloride accelerating admixtures

11.2.2 Calcium chloride—Calcium chloride is sometimes used as an accelerating admixture that reduces the time of set and increases the rate of early-age strength development of concrete. The use, effects, and maximum limits on total calcium chloride content are discussed in ACI 212.3R, ACI 201.2R, ACI 332, and Shideler (1952). When in the presence of sufficient moisture and oxygen, CaCl₂ has the potential to induce corrosion of embedded reinforcing bar or metal in concrete. The amount of water-soluble chloride ion should consider all other sources of chloride ions in the concrete mixture. ACI 318 and ACI 332 provides the maximum water-soluble chloride ion content based on exposure class.

11.2.3 Accelerating admixtures containing CaCl₂—Water-reducing accelerating admixtures conforming to ASTM C494/C494M Type E accelerate the time of set and strength gain and reduce the necessary water content of the mixture. Many Type E admixtures usually produce less than 0.25 percent water-soluble chloride by weight of total cementitious material when used at recommended dosage rates. Type E admixtures may contain water-soluble chloride ion. When used at recommended dosage rates, the water-soluble chloride-ion content is typically less than 0.25 percent by weight of total cementitious materials. Consult with the admixture manufacturer to determine the percentage of water-soluble chloride ion by weight of total cementitious materials that a specific accelerating admixture contributes. Type E chemical admixtures significantly improve strength gain at 24 hours and can provide early-age strengths comparable to some concrete made with Type III cements.
11.2.4 Nonchloride accelerating admixtures—The use of nonchloride accelerating admixtures has become prevalent when the potential for corrosion of embedded metals exists. Nonchloride accelerating admixtures conform to either ASTM C494/C494M Type C or E. The term “nonchloride” does not assure the admixture is 100 percent chloride-free, as many nonchloride accelerators contain chloride ion concentrations up to 500 parts per million (5 × 10⁻³ percent). Nonchloride accelerator that conforms to ASTM C494/C494M Type C or E could induce corrosion of embedded steel at high doses. Consult with the admixture manufacturer to obtain long-term data indicating that the product is noncorrosive at a specific dosage rate.

11.3—Cold weather admixture systems (CWASs)

11.3.1 Background—The use of CWASs dates back to the 1950s when Soviet scientists reported early success in chemically depressing the liquidus temperature point of concrete mixing water (Korhonen 1990). In the 1990s the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL), the Federal Highway Administration (FHWA), several DOTs, and private industry developed CWASs with commercially available admixtures, which protected concrete down to 23°F (−5°C) (Korhonen and Brook 1996; Korhonen et al. 1997). In 2006, the ASTM C1622/C1622M standard specification for CWAS was published. This specification covers CWASs to be added to hydraulic-cement concrete when the temperature of the concrete immediately after placement will be as low as 23°F (−5°C).

11.3.2 ASTM C1622/C1622M—ASTM C1622/C1622M defines a cold weather admixture system (CWAS) as an admixture or group of admixtures that depresses the freezing point of mixing water and increases the hydration rate of cement in concrete. The term “antifreeze admixture” is often used interchangeably with the term “CWAS.” The ASTM C1622/C1622M test procedure includes a control concrete temperature at time of casting of 68 to 77°F (20 to 25°C) and test concrete temperature at time of casting of 57 ± 3°F (14 ± 2°C). Test concrete mixtures are then placed into a low-temperature environment so that, within 8 hours, the temperature at the center of the specimen is 23 ± 2.0°F (−5 ± 1°C). Test concrete mixtures are kept in this environment until an age of 7 days, and then they are cured per ASTM C192/C192M. The ASTM C1622/C1622M plastic and hardened tests include slump; air; unit weight; time of set; 7-, 28-, 90-day compressive strength; length change; and resistance to freezing-and-thawing cycles.

A maximum initial time of set of 200 percent of the control is required for a CWAS to meet ASTM C1622/C1622M cold weather admixture specification. In addition, minimum compressive strength relative to control is as follows: 7-day compressive strength ≥ 40 percent of control; 28-day compressive strength ≥ 80 percent of control; 90-day compressive strength ≥ 90 percent of control. Length change and resistance to freezing and thawing are identical to the ASTM C494/C494M specification. Because the ASTM C1622/C1622M specification was published in 2006, several combinations of commercially high dosage rates of nonchloride accelerators and Type A water-reducing admixtures have been tested and met ASTM C1622/C1622M specifications. These admixture systems have achieved the specification primarily by increasing the hydration rate of cement in concrete. In addition, research has shown that incorporating commercially available glycol-based shrinkage-reducing admixtures in conjunction with nonchloride accelerators will act as a CWAS. Glycol-based shrinkage-reducing admixtures slightly reduce the liquidus temperature of water in fresh concrete (Korhonen 1990).

11.4—Rapid setting cements

Some modified portland cements and other inorganic cements will set and achieve rapid strength development at ambient temperatures of 20°F (−7°C) (Nawy et al. 1987). Various rapid-setting cements used in concrete cast and cured for 24 hours at 20°F (−7°C) achieved compressive strengths ranging from 1700 psi (12 MPa) to more than 8000 psi (55 MPa).

CHAPTER 12—REFERENCES

ACI committee documents and documents published by other organizations are listed first by document number, full title, and year of publication followed by authored documents listed alphabetically.

American Concrete Institute

ACI 201.2R-08—Guide to Durable Concrete
ACI 207.1R-05—Guide to Mass Concrete
ACI 207.4R-05—Cooling and Insulating Systems for Mass Concrete
ACI 212.3R-16—Report on Chemical Admixtures for Concrete
ACI 228.1R-03—In-Place Methods to Estimate Concrete Strength
ACI 302.1R-15—Guide to Concrete Floor and Slab Construction
ACI 306.1-90—Standard Specification for Cold Weather Concreting
ACI 318-14—Building Code Requirements for Structural Concrete and Commentary
ACI 332-14—Residential Code Requirements for Structural Concrete and Commentary
ACI 347R-14—Guide to Formwork for Concrete
ACI 347.2R-05—Guide for Shoring/Reshoring of Concrete Multistory Buildings

ASTM International

ASTM C39/C39M-16—Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens
ASTM C192/C192M-13a—Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory
ASTM C309-11—Standard Specification for Liquid Membrane-Forming Compounds for Curing Concrete
ASTM C494/C494M-13—Standard Specification for Chemical Admixtures for Concrete
ASTM C597-09—Standard Test Method for Pulse Velocity through Concrete
ASTM C803/803M-03(2010)—Standard Test Method for Penetration Resistance of Hardened Concrete
ASTM C873/C873M-15—Standard Test Method for Compressive Strength of Concrete Cylinders Cast in Place in Cylindrical Molds
ASTM C900-15—Standard Test Method for Pullout Strength of Hardened Concrete
ASTM C918/C918M-13—Standard Test Method for Measuring Early-Age Compressive Strength and Projecting Later-Age Strength
ASTM C1064/C1064M-12—Standard Test Method for Temperature of Freshly Mixed Hydraulic-Cement Concrete
ASTM C1074-11—Standard Practice for Estimating Concrete Strength by the Maturity Method
ASTM C1622/C1622M-10—Standard Specification for Cold-Weather Admixture Systems

Portland Cement Association

IS128—Concrete for Massive Structures

Authored documents


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