ACI 306R-10

Guide to Cold Weather Concreting

Reported by ACI Committee 306

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Guide to Cold Weather Concreting

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American Concrete Institute
38800 Country Club Drive
Farmington Hills, MI 48331
U.S.A.
Phone: 248-848-3700
Fax: 248-848-3701

www.concrete.org

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Stephen C. Morrical
Chair

Kevin A. MacDonald
Vice Chair

Kim D. Basham	John P. Gnaedinger	Timothy J. Lickel	Richard W. Melnechuk
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D. Gene Daniel	Eric D. King	Zhongguo John Ma	Valery Tokar
David J. Elmer			

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The objectives of cold weather concreting practices are to prevent damage to concrete due to freezing at early ages, ensure that the concrete develops the required strength for safe removal of forms, maintain curing conditions that foster normal strength development, limit rapid temperature changes, and provide protection consistent with the 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 produced, placed, and protected. This guide provides information for the contractor to select the best methods to satisfy the minimum cold weather concreting requirements.

This guide discusses: concrete temperature during mixing and placing, temperature loss during delivery, preparation for cold weather concreting, protection requirements for concrete that does not require construction supports, estimating strength development, methods of protection, curing requirements, 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.

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.

CONTENTS

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CHAPTER 1—INTRODUCTION

Cold weather exists 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 time required to prevent concrete from being affected by exposure to cold weather. Concrete placed during cold weather will develop sufficient strength and durability to satisfy the intended service requirements when it is properly produced, placed, and protected. The necessary degree of protection increases as the ambient temperature decreases.

If requirements for cold weather concreting are needed in specification form, reference ACI 306.1. If necessary, add appropriate modifications to the contract documents after consulting the specification checklist.

This guide provides the necessary information for the contractor to select the best methods to satisfy the minimum cold weather concreting requirements.

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

M = maturity factor, degree-hour
T = temperature of concrete, °F (°C)
T_a = temperature of coarse aggregate, °F (°C)
T_c = temperature of cement, °F (°C)
T_d = temperature drop to be expected during a 1-hour delivery time, °F (°C). (This value should be added to t_r to determine the required temperature of concrete at the plant.)
T_o = datum temperature, °F (°C)
T_s = temperature of fine aggregate, °F (°C)
T_w = temperature of added mixing water, °F (°C)
t_a = ambient air temperature, °F (°C)
t_r = concrete temperature required at the job, °F (°C)
W_a = saturated surface-dry weight of coarse aggregate, lb (kg)
W_c = weight of cement lb (kg)
W_s = saturated surface-dry weight of fine aggregate, lb (kg)
W_w = weight of mixing water, lb (kg)
W_{wa} = weight of free water on coarse aggregate, lb (kg)
W_{ws} = weight of free water on fine aggregate, lb (kg)
w/cm = water-cementitious material ratio
Δt = duration of curing period at temperature T, degree-hour

2.2—Definitions

ACI provides a comprehensive list of definitions through an online resource, "ACI Concrete Terminology," http://terminology.concrete.org. Definitions provided herein complement that resource.

admixture—a material other than water, aggregates, cementitious materials, and fiber reinforcement, used as an ingredient of a cementitious mixture to modify its freshly mixed, setting, or hardened properties and that is added to the batch before or during its mixing.

backshores—shores placed snugly under a concrete slab or structural member after the original formwork and shores have been removed from a small area without allowing the entire slab or member to deflect or support its own mass or existing construction loads.

carbon monoxide—a molecular gas at STP (standard temperature and pressure) consisting of one atom of carbon and one of oxygen, often the product of burning organic materials in a low-oxygen environment.

carbonation—the reaction between carbon dioxide and a hydroxide or oxide to form a carbonate, especially in cement paste, mortar, or concrete; the reaction with calcium compounds to produce calcium carbonate.

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 required to prevent concrete from being affected by exposure to cold weather.

concrete, lightweight—concrete having a density of approximately 90 to 115 lb/ft^3 (1440 to 1840 kg/m^3), usually achieved by using lightweight coarse aggregate, lightweight fine aggregate, or both.

concrete, normalweight—concrete having a density of approximately 150 lb/ft^3 (2400 kg/m^3), made with normal-density aggregates.

corrosion—destruction of metal by a chemical, electro-chemical, or electrolytic reaction within its environment.

crack, plastic-shrinkage—surface crack that occurs in concrete prior to initial set.

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.

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.

post-tensioning—method of prestressing in which prestressing steel is tensioned after concrete has hardened.

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

reaction, alkali-aggregate—a generally deleterious dissolution and swelling of components in aggregates in the presence of pore solutions comprising alkali hydroxides; the reaction products may cause expansion and cracking of concrete.

reshore—a temporary support placed against the bottom of a slab or other structural member immediately after the forms and original shores have been removed.

saturation—as applied to aggregate or concrete: the condition such that no more liquid can be held or placed within it.

shore—a temporary support for formwork, fresh concrete, and construction loads or for recently built structures that have not developed full design strength; also called prop, tom, post, and strut.

strength, concrete compressive—the measured maximum resistance of a concrete specimen to axial compressive loading; expressed as force per unit cross-sectional area.

temperature—a measure of the average kinetic energy of the particles in a sample of matter, expressed in terms of units or degrees designated on a standard scale. The temperature of concrete is measured in accordance with ASTM C1064/C1064M.

CHAPTER 3—OBJECTIVES, PRINCIPLES, AND ECONOMY

3.1—Objectives

The objectives of cold weather concreting practices are as follows:

3.1.1 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. Under such conditions, the degree of saturation falls below the critical level (the degree of water saturation where a single cycle of freezing causes damage) 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;

3.1.2 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;

3.1.3 Maintain curing conditions that foster normal strength development without using excessive heat and without causing critical saturation of the concrete at the end of the protection period;

3.1.4 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 (refer to Chapter 7), gradually remove insulation or other protection so the surface temperature decreases gradually during the subsequent 24-hour period (refer to Section 7.5); and

3.1.5 Provide protection consistent with the intended serviceability of the structure. Concrete structures are intended for many years of use. 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 indiscriminate use of excessive calcium chloride ($CaCl_2$) is not serviceable if the concrete cracks excessively in later years because of disruptive internal expansion due to alkali-aggregate reaction or of possible corrosion of reinforcement (refer to Section 11.2). Short-term 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 Section 3.1. The practices and procedures in this guide stem from the following principles concerning cold weather concreting:

- 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 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 specific strength must be attained in less time;

- 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 may be required to maintain the concrete temperature (refer to Chapters 7 and 8);
- Except within heated protective enclosures, little or no external supply of moisture is required during cold weather curing (refer to Chapter 10); and
- Under certain conditions, $CaCl_2$ should not be used to accelerate setting and hardening because of increased chances of corrosion of metals embedded in concrete or other adverse effects (refer to 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

Experience shows the overall costs of adequate protection for cold weather concreting are not excessive, considering what is required and the resulting benefits. 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 can cause immediate destruction or permanently weakened concrete. Therefore, if cold weather concreting is performed, adequate planning, protection from low temperatures, and proper curing are essential.

CHAPTER 4—GENERAL REQUIREMENTS

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 in clear terms what cold weather concreting methods will be used. This guide provides a basis for the contractor to select specific methods to satisfy the minimum requirements during cold weather concreting.

Plans to protect fresh concrete from freezing and to maintain temperatures above the recommended minimum values should be made well before freezing temperatures are expected to occur. Equipment and materials should be at the work site before cold weather is likely to occur, not after concrete is placed and its temperature approaches the freezing point.

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, take precautions to protect all concrete surfaces from unexpected freezing for at least the first 24 hours after placement. 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. Continue protection and curing long enough, and at a temperature recommended by Table 5.1, to produce the strength specified for form removal or structural safety (refer to 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 and dosage, use of accelerators, and the service category.

The recommended minimum placement temperatures in Table 5.1 apply to normalweight concrete. While placement temperatures of lightweight concrete are equivalent to that of normalweight concrete, experience indicates that freshly mixed lightweight concrete loses heat more slowly than freshly mixed normalweight concrete. Lighter-weight insulating concretes lose heat even more slowly. When exposed to freezing temperatures, however, some concretes are still susceptible to damage from surface freezing.

Concrete temperature during placement should be near the minimum temperatures in Table 5.1. Placement temperatures should not be higher than these minimum values by more than 20°F (11°C). Take advantage of the opportunity provided by cold weather to place low-temperature concrete. Concrete placed at lower temperatures [40 to 55°F (5 to 13°C)], 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 subject to less thermal cracking than similar concrete placed at higher temperatures. Placement of higher temperature concrete may expedite finishing in cold weather, but may degrade long-term concrete properties.

4.4—Temperature records

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

- Concrete corners and edges are vulnerable to freezing and usually more difficult to maintain at the required temperature. Monitor the concrete surface temperature in these areas to evaluate and verify the effectiveness of the protection provided;
- Monitor internal temperature of concrete to ensure that excessive heating does not occur (refer to Section 9.4). For this, expendable thermistors or thermocouples cast in the concrete may be used;
- 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 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-recording devices should be left in place throughout the protection period; and

- 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 corners, edges, and in thin sections. Combustion heaters should be vented and not be permitted to directly heat or dry the concrete. Fresh concrete surfaces exposed to carbon dioxide, resulting from the use of salamanders or other combustion heaters that exhaust flue gases into an enclosed area, may be damaged by carbonation of the concrete. Carbonation may result in soft surfaces or surface crazing, depending on the concentration of carbon dioxide, the concrete temperature, and the relative humidity (refer to Section 9.4). Carbon monoxide, which can result from partial combustion, and high levels of carbon dioxide (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 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—Finishing air-entrained slabs

For steel-troweled floor and slab construction, air-entrained concrete should not be specified. If during construction, but after the cold weather protection period, the concrete is likely to be exposed to cycles of freezing and thawing while saturated, air entrainment may be necessary even though the concrete will not be exposed to freezing and thawing in service. Where a hard-troweled finish is required, 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% (ACI 301). The water-cementitious material ratio (*w/cm*) should not exceed the limits recommended in ACI 201.2R, and the concrete should not be allowed to freeze and thaw in a saturated condition before developing a compressive strength of 3500 psi (24 MPa). New sidewalks and other flatwork exposed to melting snow and freezing should be air entrained and protected from freezing until attaining at least 3500 psi (24 MPa).

4.7—Concrete workability

For flatwork in cold weather, lower-slump concrete with a lower-than-normal slump minimizes excessive bleed water and allows earlier setting. During cold weather, bleed water may remain on the surface for extended periods, interfering with or prolonging finishing operations. If bleed water is finished into the concrete, the resulting surface will have lower strength and be prone to dusting and deterioration. During cold weather, proportion the concrete mixture to minimize bleeding. If bleed water is present, skim it off before troweling by using a rope or hose.

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 Section 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 according to ASTM C1064/C1064M. The more massive the concrete section, the less rapidly it loses heat. Lower minimum placement temperatures are recommended for larger concrete sections, and for massive structures, it is especially beneficial to have low placement temperatures (ACI 207.1R). Concrete temperatures much higher than the Line 1 values do not result in a proportionally longer protection against freezing because the rate of heat loss is greater for larger temperature differentials.

Higher temperatures require more mixing water, increase the rate of slump loss, may cause quick setting, and increase thermal contraction. Rapid moisture loss from exposed surfaces of flatwork may 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). Keep the temperature of concrete as placed as close to the recommended minimum value as practicable. Placement temperatures should not be higher than the minimum values by more than 20°F (11°C).

If early-age strength is not critical, several admixture combinations can be used to produce a low-temperature admixture system that reduces the freezing temperature of a concrete mixture. This practice produces reasonable long-term strengths at curing temperatures lower than those presented in Table 5.1. Korhonen (2002) presents one admixture combination that produces adequate results for many applications. As the available research in this area is limited, produce and cure trial mixtures under the expected environmental conditions. Use these trial mixtures to ensure

Table 5.1—Recommended concrete temperatures

		Section size, minimum dimension			
		< 12 in. (300 mm)	12 to 36 in. (300 to 900 mm)	36 to 72 in. (900 to 1800 mm)	> 72 in. (1800 mm)
Line	**Air temperature**	**Minimum concrete temperature as placed and maintained**			
1	—	55 F (13 C)	50 F (10 C)	45 F (7 C)	40 F (5 C)
		Minimum concrete temperature as mixed for indicated air temperature*			
2	Above 30°F (–1°C)	60°F (16°C)	55°F (13°C)	50°F (10°C)	45°F (7°C)
3	0 to 30°F (–18 to –1°C)	65°F (18°C)	60°F (16°C)	55°F (13°C)	50°F (10°C)
4	Below 0 F (–18 C)	70 F (21 C)	65 F (18 C)	60 F (16 C)	55 F (13 C)
5	—	**Maximum allowable gradual temperature drop in first 24 hours after end of protection**			
		50°F (28 C)	40° (22 C)	30°F (17 C)	20°F (11 C)

*For colder weather, a greater margin in temperature is provided between concrete as mixed and required minimum temperature of fresh concrete in place.

the workability and strength development of the mixture for the application.

5.2—Mixing temperature

Lines 2, 3, and 4 of Table 5.1 show the recommended minimum temperature of concrete at mixing time. As the ambient air temperature decreases, increase the concrete temperature during mixing to offset the heat lost in the interval between mixing and placing. The mixing temperature should not be more than 15°F (8°C) above the values in Lines 2, 3, and 4. While it is difficult to uniformly heat aggregates to a predetermined temperature, mixing water temperature can be adjusted easily by blending hot and cold water to obtain a concrete temperature within 10°F (5°C) of the required temperature.

5.3—Heating mixing water

Mixing water should be available at a consistent, regulated temperature, and in a quantity to avoid appreciable fluctuations in concrete temperature from batch to batch. Because the temperature of concrete affects the rate of slump loss and may affect admixture performance, temperature fluctuations can result in variable characteristics between batches.

Premature contact of very hot water with concentrated quantities of cement has been reported to cause flash set and cement balls in truck mixers. When using water above 140°F (80°C), it may be necessary to adjust the order in which ingredients are blended. It may be helpful to add the hot water and coarse aggregate before the cement, and to stop or slow the addition of water as the cement and aggregate are loaded.

If batching the cement separately from the aggregate, mixing may be difficult. To facilitate mixing, place 3/4 of the added hot water in the drum before the aggregates or with them. To prevent packing at the end of the mixer, add coarse aggregate first. Add the cement after the aggregates. As the final ingredient, place the remaining 1/4 of the mixing water into the drum at a moderate rate.

Water with a temperature as high as the boiling point may be used provided the resulting concrete temperatures are within the limits discussed in Section 5.2 and no flash setting occurs. If hardened concrete samples suggest the air-entraining admixture loses effectiveness, it is likely due to an initial contact with hot water. Addition of the admixture to the batch after the water temperature is lowered from contact with the cooler, solid materials will maintain 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). If the coarse aggregate is dry and free of frost, ice, and frozen lumps, adequate temperatures of freshly mixed concrete can be reached by increasing the sand temperature, which seldom has to be above 105°F (40°C), if mixing water is heated to 140°F (60°C). 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 should 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.

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 as much as practical to maintain a uniform heat distribution and to prevent ice crust formation. When heating aggregates by steam jets, troublesome moisture variation may occur, but this is the most thermally efficient procedure to heat aggregate. 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 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 batching 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

Heat aggregates sufficiently to eliminate ice, snow, and frozen lumps of aggregate. Often, frozen lumps as large as 3 in. (76 mm) survive mixing and remain in the concrete after placing. Stockpiles of aggregate should be heated with steam after being covered with tarps to contain the energy. The use of hot water in the mix to thaw the aggregate should be cautioned to avoid upsetting the *w/cm* from too much water. Thawing aggregates will add to the overall water content. 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. Heat materials uniformly because temperature variation significantly alters the water requirement, air entrainment, rate of setting, 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. 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 final temperature of the concrete mixture may be estimated from the formula

$$T = \frac{[0.22(T_sW_s + T_aW_a + T_cW_c) + T_wW_w + T_sW_{ws} + T_aW_{wa}]}{[0.22(W_s + W_a + W_c) + W_w + W_{wa} + W_{ws}]} \quad (5\text{-}1)$$

Equation (5-l) 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. (5-1) should be modified to consider the heat required 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. (5-1) by substituting the following expressions for T_sW_{WS} or T_aW_{wa}, or both, depending on whether the fine aggregate or coarse aggregate, or both, are below 32°F (0°C).

For inch-pound units:

substitute $W_{ws}(0.5T_s - 128)$ for T_sW_{ws} (5-2)

substitute $W_{wa}(0.5T_a - 128)$ for T_aW_{wa} (5-3)

For SI units:

substitute $W_{ws}(0.5T_s - 80)$ for T_sW_{ws} (5-4)

substitute $W_{wa}(0.5T_a - 80)$ for T_aW_{wa} (5-5)

In Eq. (5-2) through (5-5), 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. (5-6) through (5-8).

For revolving drum mixers:

$$T = 0.25(t_r - t_a) \quad (5\text{-}6)$$

For covered-dump body:

$$T = 0.10(t_r - t_a) \quad (5\text{-}7)$$

For open-dump body:

$$T = 0.20(t_r - t_a) \quad (5\text{-}8)$$

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). From Eq. (5-6)

$$T = 0.25(50 - 20) = 7.5°\text{F } (4.2°\text{C})$$

Therefore, make allowance for a 7.5°F (4.2°C) temperature drop, and the concrete at the plant should have a temperature of at least (50 + 7.5°F), or about 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 be revolved except for initial mixing and again briefly at the time of discharge. Assuming that Eq. (5-7) represents this situation best, the temperature drop is

$$T = 0.10(50 - 20) = 3°\text{F } (1.7°\text{C})$$

Make provisions for a concrete temperature of (50 + 3°F), or 53°F (12°C), at the plant.

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

The procedures below are valid for thermal insulation and low-temperature admixture system approaches to concrete placement.

6.1—Preparation of surfaces in contact with fresh concrete

Preparation before concrete is placed requires a temperature increase of the formwork, reinforcement, and other surfaces that will contact fresh concrete so the temperature of the freshly placed concrete will not decrease below the minimums as placed and maintained (Table 5.1). There are many techniques for warming formwork and embedded items, including heated enclosures, electric blankets, hydronic heating systems, or other acceptable means. Best practice indicates that all surfaces should be above the freezing temperature of water. However, take care to limit surface temperatures to no more than 10°F (5°C) greater or 15°F (8°C) less than that of the concrete to avoid inconsistent setting, rapid moisture loss, and plastic shrinkage cracking.

All surfaces to receive concrete and all spaces to be filled with concrete should be free of snow and ice before placement. Follow the removal of ice or frost with the removal of standing water so that it is not incorporated into the fresh concrete.

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 poor concrete quality adjacent to the embedment. A study of No. 9 (No. 29) bars and concrete pipes filled with concrete, using finite element models, was reported in 1985 (Suprenant and Basham 1985). Based on this study, any embedment having a cross-sectional area greater than 1 in.^{2} (650 mm^2) should be no colder than 10°F (–12°C) immediately before placing the concrete at 56°F (13°C) around it. Ideally, the embedment should be heated to the temperature of the concrete immediately before concrete placement.

The architect/engineer should identify those portions of the embedment that pose potential problems.

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

Concrete should not be placed on frozen subgrade. Remove all frost before placing the concrete and recompact thawed soil disturbed by frost. Placement of insulation over the subgrade, or provision of heat, is required to remove any frost in the soil and to raise the subgrade temperature above 32°F (0°C). An appropriate provision for heat should be selected based on the amount of frost depth and temperature difference with the air. Once thawed and recompacted, insulation should be placed directly over the subgrade to protect it from refreezing.

When the concrete temperature is more than 10°F (5°C) cooler or 5°F (8°C) warmer than the subgrade, differential rates of setting between the top and bottom of the slab may result in various surface defects including plastic shrinkage cracking, blistering, and delaminations. Concrete placed in these conditions may require modified finishing practices to compensate for differential rates of setting between the top and the bottom of the concrete. This may include delaying finishing operations, using lighter finishing equipment, and taking steps to prevent moisture evaporation.

CHAPTER 7—PROTECTION AGAINST FREEZING AND PROTECTION 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 require construction supports are those elements that will not be required to provide significant structural performance during the construction schedule that would otherwise be delayed by the lack of design strength due to the frozen conditions. Some common examples of these elements include slab-on-ground systems such as road or bridge decks, driveways, sidewalks, patios, and residential slabs, as well as many residential foundation walls and footings.

7.1—Protection methods

Protect concrete from freezing as soon as practicable after placement, consolidation, and finishing. 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 water-cementitious material ratio (*w/cm*), increasing the cement content, changing the pozzolan quantity, 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 by at least 20%.

7.2—Protection period

Effective protection allows the concrete to gain strength at a normal rate and prevents the concrete from early-age damage by freezing of 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 7.1.

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

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 may be damaged. Give consideration to 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 (refer to Section 4.6). In these cases, continue protection to prevent damage from repeated cycles of freezing and thawing when critically saturated.

7.3—Protection for strength gain

When there are early-age strength requirements, it is necessary to extend the protection period beyond the minimum duration given in Table 7.1. Where early-age strength is not specified, maintain the concrete at temperatures in Table 5.1 for the time period shown in Table 7.1. Where early-age strength is specified, maintain the element at the temperatures in Table 5.1 until the required 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. The four defined conditions detailed below impact minimum recommended insulation period.

1. *No load, not exposed*: Elements will not be exposed to freezing conditions in service and will not carry significant loads during the curing period (refer to Line 1 in Table 7.1). Examples of this condition could 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 in service;

2. *No load, exposed*: Elements will not carry significant loads during the curing period and will be exposed to freezing and thawing in service (refer to Line 2 in Table 7.1). Examples of this condition could include massive piers and dams that have surfaces exposed to freezing and weathering;

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 (refer to Line 3 in Table 7.1); and

4. *Full load*: Elements that need reshoring to withstand construction loads before they are fully cured (refer to Line 4 in Table 7.1. and Chapter 8). This would include plain or reinforced structural concrete.

At the end of the protection period, gradually cool the concrete. The temperature drop of concrete surfaces should not exceed the rates indicated in Table. 5.1. Accomplish this by slowly reducing heat sources or allowing insulation to remain until the concrete has essentially reached equilibrium with the mean ambient temperature. As shown in Table 5.1, the maximum allowable cooling rates for mass concrete surfaces are lower than for thinner members because mass concrete members develop higher thermal gradients and, thus, are more susceptible to surface cracking.

7.4—Temperature drop after removal of protection

At the end of the protection period, concrete should be cooled gradually to reduce crack-inducing differential strains between the interior and exterior of the structure. The temperature drop of concrete surfaces should not exceed the rates indicated in Table 5.1. This can be accomplished by slowly reducing sources of heat, or by allowing insulation to remain 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.

Table 7.1—Length of protection period for concrete placed during cold weather

Line	Service condition	Protection period at minimum temperature indicated in Line 1 of Table 5.1, days*	
		Normal-set concrete	Accelerated-set concrete
1	No load, not exposed	2	1
2	No load, exposed	3	2
3	Partial load, exposed	6	4
4	Full load	Refer to Chapter 8	

*A day is a 24-hour period.

7.5—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 because mass concrete members develop higher thermal gradients and, thus, are more susceptible to surface cracking. For example, use Fig. 7.1 to determine the maximum allowable difference between the concrete temperature in a wall and the ambient air temperature (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 FOR STRUCTURAL CONCRETE REQUIRING CONSTRUCTION SUPPORTS

8.1—Introduction

For structural concrete members such as elevated slabs, beams and girders where considerable design strength should be attained before safe removal of forms and shores, provide protection time beyond the minimums given in Table 7.1, as these minimum times do not allow adequate strength gain. Base the criteria for removal of forms and shores from structural concrete on the in-place concrete strength rather than on specified time duration. Recommendations in this chapter are based on job conditions meeting the requirements given in Section 8.10.

8.2—Field-cured cylinders

Field-cured cylinders, as described in ASTM C31/C31M, are intended to be cured with the structure and typically represent the lowest likely strength of the structure. In accor-

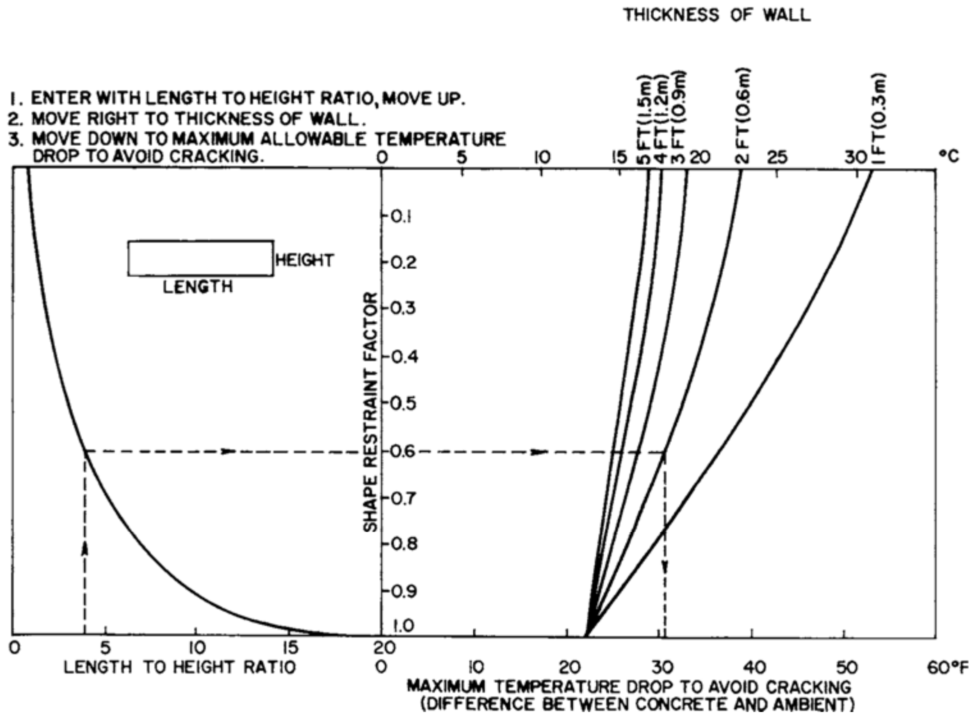

Fig. 7.1—Graphical determination of safe differential temperature for walls (Mustard and Ghosh 1979).

dance with ASTM C31/C31M, cast the cylinders on site and protect them from damage caused by vibration or movement until placing them in the curing environment of the member represented by the cylinders. For flatwork, cylinders can be cast in the slab and pulled out later to test for strength (ASTM C873/C873M).

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/C803M) is a technique that involves placing pins in the concrete using a powder-actuated tool. Pulse velocity measurements (ASTM C597) and rebound hammer measurements (ASTM C805/C805M) 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 result in a specific strength for a given concrete mixture. There are a number of ASTM test methods that deal with maturity testing (ASTM C918/C918M, ASTM C1074). The maturity concept as originally defined by Saul (1951) considers the relationship of time, temperature, and strength gain. The equivalent age concept (Freisleben Hansen and Pedersen 1977), based on principles of chemical kinetics, applies a nonlinear reaction response that has been 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 the anchorage location for post-tensioning tendons, the centroid of the area of compression steel at the maximum deflection point of a beam, and at the edges and corners of slabs. 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 differing amounts of cementitious material, water-cement ratios, and admixtures, 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 factor 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 factors 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 factor at that time and read the corresponding strength on the strength-maturity factor curve. The in-place maturity factor at a particular location is determined by measuring the temperature of the concrete at close time intervals and using Eq. (8-1) to sum the successive products of the time intervals and the corresponding average concrete temperature above the datum temperature.

$$M = \Sigma(T - T_o)\Delta t \quad (8\text{-}1)$$

where

M = maturity factor, degree-hour

T = temperature of concrete, °F (°C)

T_o = datum temperature, °F (°C)

Δt = duration of curing period at temperature T, degree-hour

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 factor 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. 8.1. They automatically compute and display the maturity factor in degree-hours.

Strength prediction based on the maturity factor assumes the in-place concrete has the same strength potential as the concrete used to develop the strength-maturity factor curve. Before removing forms or shores, it is necessary to determine whether the in-place concrete has the assumed strength potential by performing additional tests such as:

- Testing standard-cured cylinders at early ages;
- Using accelerated strength tests as described in ASTM C684;
- Testing field-cured cylinders for which the maturity factor has been monitored; and
- Using one of the in-place tests listed in Section 8.3.

8.4.1 *Example illustrating the maturity factor 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 factor curve (Fig. 8.2) was established. A record of the in-place concrete temperature was maintained as indicated in Columns 2 and 3 of Table 8.1. 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 by subtracting the datum temperature of 23°F (–5°C) (Column 5) and the cumulative maturity factors at different ages (Column 8). Based on the strength-maturity factor curve (Fig. 8.2), 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.

Fig. 8.1—Maturity meter.

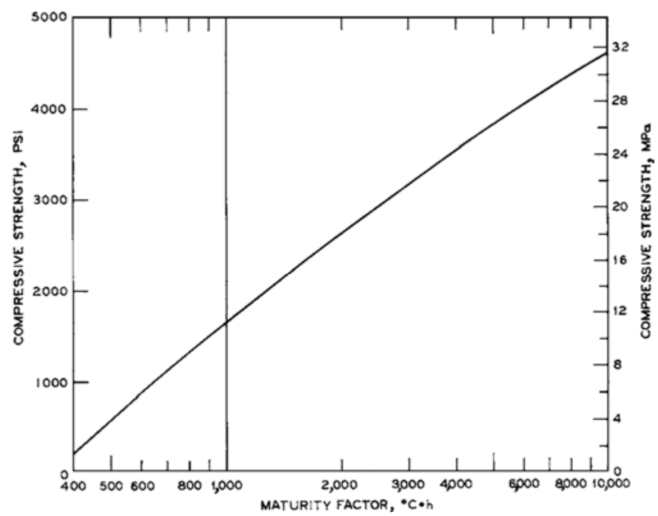

Fig. 8.2—Example of a strength-maturity factor relationship for laboratory-cured cylinders (73°F [22.8°C]).

8.5—Attainment of design strength

Generally, there is little opportunity for further curing of structural concrete beyond that provided initially. Figure 8.3 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, early strengths high enough to assure later attainment of design must be attained before temporarily supported structural concretes can be safely released from cold weather protection.

8.6—Increasing early strength

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

- Initial temperature of the concrete when placed;
- Temperature at which the concrete is maintained after placing;
- Type of cement;
- Type and amount of accelerating admixture or other admixtures used; and
- Conditions of protection and curing.

Economic considerations may dictate an accelerated construction schedule even though the resulting concrete

Table 8.1—Calculation of maturity factor and estimated in-place strength

1	2	3		4		5		6	7		8		9	
Date	Elapsed time h, h	Temperature in structure		Average temperature in structure T		Column 4 – T_o*		Time interval Δt, h	Column 5 × Column 6		Maturity factor M Σ Column 8		Corresponding compressive strength	
		°F	°C	°F	°C	°F	°C		°F-h	°C-h	°F-h	°C-h	psi	MPa
09/01	0	50	10	—	—	—					—		—	—
	12	50	10	50	10	27	15	12	320	180	320	180	—	—
09/02	24	50	10	50	10	27	15	12	320	180	640	360	—	—
	30	46	8	48	9	25	14	6	150	80	790	440	400	2.5
09/03	48	48	9	47	8	24	13	18	430	230	1220	670	1100	7.5
	60	46	8	47	8	24	13	12	290	160	1510	830	1400	9.5
09/04	72	44	7	45	7	22	12	12	260	140	1770	970	1600	11
09/08	168	42	6	43	6	20	11	96	1920	1060	3690	2030	2600	18
09/11	240	42	6	42	6	19	11	72	1370	790	5060	2820	3100	21.5
09/14	312	42	6	42	6	19	11	72	1370	490	6430	3610	3400	23.5

*The datum temperature T_o is 23°F (–5°C).

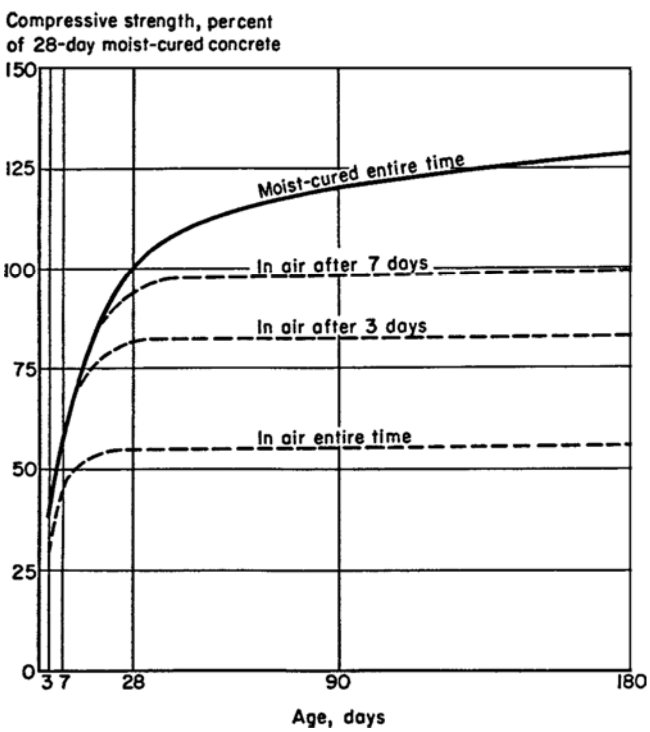

Fig. 8.3—Compressive strength of concrete dried in laboratory air after preliminary moist curing (Price 1951).

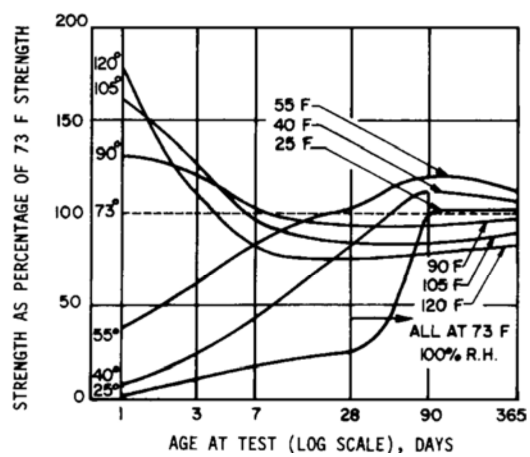

Fig. 8.4—Effect of temperature conditions on the strength development of concrete (Type I cement) (Kleiger 1958).

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:

- Increasing the temperature during protection to a level higher than indicated in Line 1 of Table 5.1, Fig. 8.4 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. 8.4 only as a guide;
- Using types and compositions of cement that exhibit higher early strength development and using higher cement content with a lower water-cement ratio (refer to Section 11.1); and
- 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 $CaCl_2$ or Type C or Type E admixtures containing $CaCl_2$.

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.

8.7—Cooling of 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 Table 5.1, Line 5 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 8.2 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:

- The in-place strength of concrete required to permit removal of forms and shores should be specified by the architect/engineer;
- Perform tests of field-cured concrete specimens or nondestructive tests of in-place concrete (refer to Sections 8.2 and 8.3);
- Nondestructive testing should be correlated with the actual concrete mixture used and verified by job-cured specimens;
- Methods to evaluate the concrete strength tests results should be completely prescribed in the specifications;
- 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; and
- The reshoring procedure, which is one of the most critical operations in formwork, should be planned in advance and reviewed by the licensed design professional. This operation should be performed so that early-age concrete members are not subjected to combined self weight and other construction loads in excess of their early-age load-carrying capacity. The early-age load capacity of a concrete member should be conservatively considered as being proportional to the in-place strength with respect to the design strength as determined by the in-place strength at the time of form removal and reshoring. Refer to ACI 347.2R for further information on shoring/reshoring operations.

8.10—Specification recommendations

Recommendations in this chapter and in Table 8.2 are based on job conditions meeting these conditions:

- The internal concrete temperature is at least 50°F (10°C) after placing the concrete. To reduce subsequent thermal contractions, exceed this temperature as little as practicable;
- Facilities are available to maintain the concrete temperature throughout the structure at 50°F (10°C) or above until protection is safely discontinued. Such facilities should incorporate, as required, the following:
  a. Suitable protection from wind and heat loss;
  b. Effective and sufficient heating equipment and personnel to maintain all parts of the concrete at the required temperature;
  c. Necessary fire protection equipment;
  d. Protection and heating to include the top surface of newly placed slabs or floors; and
  e. Venting and circulation to maintain even temperature at the top and the bottom of vertical units such as walls, piers, and columns.
- Reshores remain in place as long as necessary to safely distribute the construction loads to the lower floors. The number of tiers reshored below the tier being placed and how long the reshores remain in place should be based on reliable evidence that sufficient strength exists to safely carry the applied loads. Reliable evidence consists of a combination of calculations and compressive strength measurements before removing shores.
- Concrete is made with ASTM C150/C150M Type I, II, or III portland cement, ASTM C595/C595M cement, and ASTM C1157/C1157M cement, with or without fly ash, slag cement or silica fume.
- Proper curing is used to avoid drying of the concrete in heated enclosures (refer to Chapter 10); and
- Inspections are performed to check compliance with the plans and specifications.

Table 8.2—Duration of recommended protection for percentage of standard-cured 28-day strength*

Percentage of standard-cured 28-day strength	At 50°F (10°C), days			At 70°F (21°C), days		
	Type of cement			Type of cement		
	I	II	III	I	II	III
50	6	9	3	4	6	3
65	11	14	5	8	10	4
85	21	28	16	16	18	12
95	29	35	26	23	24	20

*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). The 28-day strength for each type of cement was considered as 100% 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.

8.11—Estimating strength development—modeling of cold weather placements

The proposed protection scheme can be modeled to predict concrete temperature-time properties. Although methods like Schmidt's method (Hoyt 1983) have been used, these models assume a constant set of thermal properties and do not allow for the inclusion of insulation.

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:

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

These assumptions are conservative. The freezing 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 as close as possible to the recommended temperatures in Line 1 of Table 5.1 and for the lengths of time recommended in Table 7.1 until the in-place strength has reached a previously established target value. The specific protection system required 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 required 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:

- *Polystyrene foam sheets*—Sheets may be cut to shape and wedged between the studs of the forms or glued into place;
- *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;
- *Insulation blankets*—Blankets should be fully moisture impervious 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;
- *Straw*—Straw is not recommended because it is bulky, highly flammable, ineffective when wet, and difficult to keep in place, especially during windy conditions; and
- *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 wet curing and prevent carbonation. Although polyethylene sheeting has a low thermal resistance (R-value), the sheeting alone can greatly reduce concrete temperature loss on cold, windy days. Sheeting 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 wet curing 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 Section 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 required insulation is greater for a long protection period than for a shorter period. Conversely, 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 9.1, 9.2, 9.3, and 9.4 and Fig. 9.1, 9.2, 9.3 and 9.4 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 required thermal resistance R, under different conditions. Use the insulation values in Table 9.5 to calculate the thickness of the chosen insulating material needed to obtain the required thermal resistance. The thermal resistance of the 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

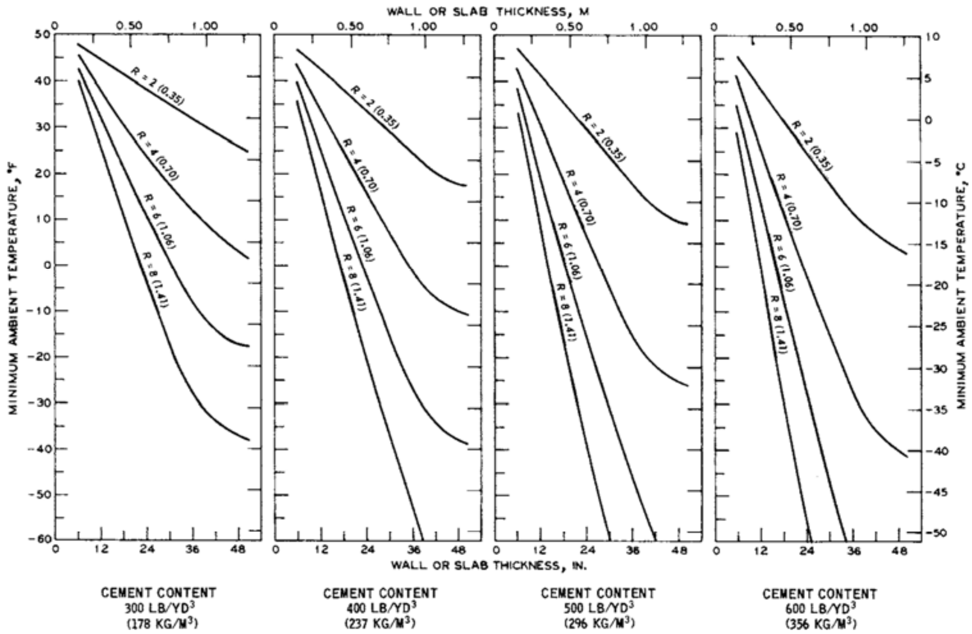

Fig. 9.1—Minimum exposure temperatures for concrete slabs above ground and walls as a function of member thickness, R*-value, and cement content. Concrete placed and surface temperature maintained at 50°F (10°C) for 7 days.*

Table 9.1—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

Wall or slab thickness, in. (m)	Minimum ambient air temperature, °F (°C), allowable when insulation having these values of thermal resistance *R*, h·ft^2·°F/BTU (m^2·K/W), is used			
	R = 2 (0.35)	*R* = 4 (0.70)	*R* = 6 (1.06)	*R* = 8 (1.41)
Cement content = 300 lb/yd^3 (178 kg/m^3)				
6 (0.15)	48 (9)	46 (8)	43 (6)	40 (4)
12 (0.30)	45 (7)	39 (4)	32 (0)	25 (–4)
18 (0.46)	41 (5)	31 (–1)	21 (–6)	11 (–12)
24 (0.61)	38 (3)	24 (–4)	10 (–12)	–2 (–19)
36 (0.91)	32 (0)	12 (–11)	–8 (–22)	–28 (–33)
48 (1.20)	26 (–3)	3 (–16)	–17 (–27)	–37 (–38)
60 (1.50)	26 (–3)	3 (–16)	–17 (–27)	–37 (–38)
Cement content = 400 lb/yd^3 (237 kg/m^3)				
6 (0.15)	47 (8)	44 (7)	40 (4)	36 (2)
12 (0.30)	43 (6)	35 (2)	26 (–3)	17 (–8)
18 (0.46)	39 (4)	25 (–4)	11 (–12)	–2 (–19)
24 (0.61)	34 (1)	16 (–8)	–2 (–19)	–20 (–29)
36 (0.91)	25 (–4)	–1 (–18)	–27 (–31)	–53 (–47)
48 (1.20)	18 (–8)	–10 (–23)	–38 (–39)	*
60 (1.50)	18 (–8)	–10 (–23)	–38 (–39)	*
Cement content = 500 lb/yd^3 (296 kg/m^3)				
6 (0.15)	47 (8)	43 (6)	38 (3)	33 (1)
12 (0.30)	42 (6)	31 (–1)	20 (–7)	9 (–13)
18 (0.46)	36 (2)	19 (–7)	2 (–17)	–15 (–26)
24 (0.61)	30 (–1)	7 (–14)	–16 (–27)	–39 (–39)
36 (0.91)	18 (–8)	–15 (–26)	–46 (–43)	–79 (–62)
48 (1.20)	10 (–12)	–25 (–32)	–60 (–51)	*
60 (1.50)	10 (–12)	–25 (–32)	*	*
Cement content = 600 lb/yd^3 (356 kg/m^3)				
6 (0.15)	46 (8)	41 (5)	35 (2)	29 (–2)
12 (0.30)	40 (4)	28 (–2)	14 (–10)	0 (–18)
18 (0.46)	33 (1)	13 (–11)	–7 (–22)	–29 (–34)
24 (0.61)	26 (–3)	–1 (–18)	–28 (–33)	–55 (–48)
36 (0.91)	12 (–11)	–27 (–31)	–66 (–54)	*
48 (1.20)	4 (–16)	–40 (–40)	*	*
60 (1.50)	4 (–16)	–40 (–40)	*	*

* << –60°F (–51°C).

of the insulation. The values shown in the tables and figures 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

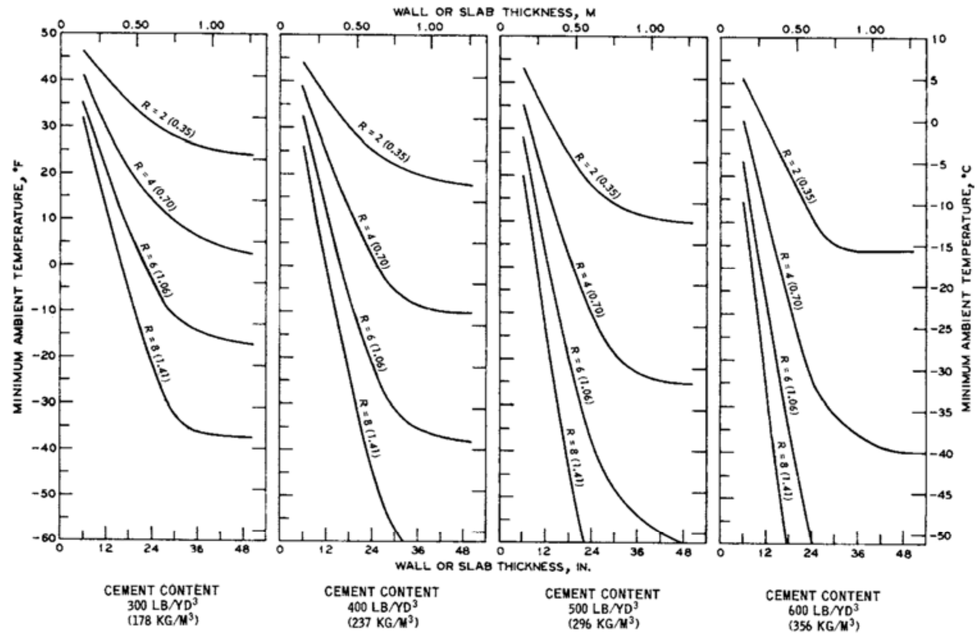

Fig. 9.2—Minimum exposure temperatures for concrete slabs above ground and walls as a function of member thickness, R-value, and cement content. Concrete placed and surface temperature maintained at 50°F (10°C) for 3 days.

Table 9.2—Minimum exposure temperatures for concrete slabs above ground and walls for concrete placed and surface temperature maintained for 50°F (10°C) for 3 days

Wall or slab thickness, in. (m)	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			
	R = 2 (0.35)	*R* = 4 (0.70)	*R* = 6 (1.06)	*R* = 8 (1.41)
Cement content = 300 lb/yd³ (178 kg/m³)				
6 (0.15)	46 (8)	41 (5)	36 (2)	32 (0)
12 (0.30)	41 (5)	31 (–1)	21 (–6)	11 (–12)
18 (0.46)	36 (2)	21 (–6)	8 (–13)	–5 (–21)
24 (0.61)	31 (–1)	14 (–10)	–3 (–19)	–21 (–29)
36 (0.91)	26 (–3)	8 (–13)	–14 (26)	–36 (–38)
48 (1.20)	26 (–3)	3 (–16)	–17 (–27)	–37 (–38)
60 (1.50)	26 (–3)	3 (–16)	–17 (–27)	–37 (–38)
Cement content = 400 lb/yd³ (237 kg/m³)				
6 (0.15)	44 (7)	38 (3)	32 (0)	26 (–3)
12 (0.30)	37 (3)	24 (–4)	12 (–11)	0 (–18)
18 (0.46)	30 (–1)	12 (–11)	–6 (–21)	–24 (–31)
24 (0.61)	25 (–4)	2 (–17)	–21 (–29)	–44 (–42)
36 (0.91)	20 (–7)	–9 (–23)	–36 (–38)	–63 (–53)
48 (1.20)	18 (–8)	–10 (–23)	–38 (–39)	*
60 (1.50)	18 (–8)	–10 (–23)	–38 (–39)	*
Cement content = 500 lb/yd³ (296 kg/m³)				
6 (0.15)	43 (6)	35 (2)	28 (–2)	20 (–7)
12 (0.30)	34 (1)	18 (–8)	3 (–16)	–12 (–24)
18 (0.46)	25 (–4)	2 (–16)	–21 (–29)	–44 (–42)
24 (0.61)	18 (–8)	–10 (–23)	–38 (–39)	–68 (–56)
36 (0.91)	12 (–11)	–23 (–31)	–60 (–51)	*
48 (1.20)	10 (–12)	–25 (–32)	*	*
60 (1.50)	10 (–12)	–25 (–32)	*	*
Cement content = 600 lb/yd³ (356 kg/m³)				
6 (0.15)	41 (5)	32 (0)	23 (–5)	14 (–10)
12 (0.30)	31 (–1)	12 (–11)	–7 (–22)	–26 (–32)
18 (0.46)	21 (–6)	–7 (–22)	–35 (–37)	–63 (–53)
24 (0.61)	11 (–12)	–24 (–31)	–59 (–51)	*
36 (0.91)	4 (–16)	–36 (–38)	*	*
48 (1.20)	4 (–16)	–40 (–40)	*	*
60 (1.50)	4 (–16)	–40 (–40)	*	*

* << –60°F (–51°C).

than 0.1. For all practical purposes, the effects of wind speed may be neglected in determining the required thickness of added insulation.

Corners and edges are particularly vulnerable during cold weather. The thickness of insulation for these parts should be approximately three times the thickness required for walls or

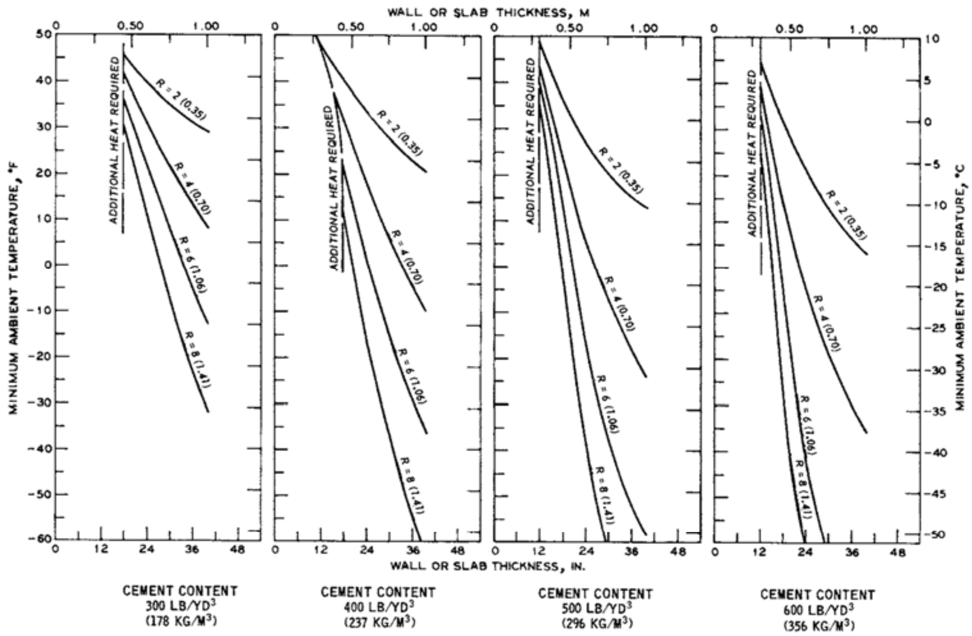

Fig. 9.3—Minimum exposure temperatures for concrete flatwork placed on ground as a function of member thickness, R-value, and cement content. Concrete placed and surface temperature maintained at 50°F (10°C) for 7 days on ground at 35°F (2°C).

Table 9.3—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)

Slab thickness, in. (m)	Minimum ambient air temperature, °F (°C), allowable when insulation having these values of thermal resistance R, h·ft^2·°F/BTU (m^2·K/W), is used: R = 2 (0.35)	R = 4 (0.70)	R = 6 (1.06)	R = 8 (1.41)
Cement content = 300 lb/yd^3 (178 kg/m^3)				
4 (0.10)	*	*	*	*
8 (0.20)	*	*	*	*
12 (0.31)	*	*	*	*
18 (0.46)	46 (8)	42 (6)	36 (2)	30 (–1)
24 (0.61)	40 (4)	31 (–1)	22 (–6)	11 (–12)
30 (0.76)	35 (2)	22 (–6)	7 (–14)	–8 (–22)
36 (0.91)	31 (–1)	13 (–11)	–5 (–21)	–23 (–31)
Cement content = 400 lb/yd^3 (237 kg/m^3)				
4 (0.10)	*	*	*	*
8 (0.20)	*	*	*	*
12 (0.31)	*	*	*	50 (10)
18 (0.46)	41 (5)	32 (0)	22 (–6)	12 (–11)
24 (0.61)	35 (2)	19 (–7)	–1 (–17)	–15 (–26)
30 (0.76)	28 (–2)	8 (–13)	–14 (–26)	–36 (–38)
36 (0.91)	23 (–5)	–4 (–20)	–29 (–34)	–54 (–48)
Cement content = 500 lb/yd^3 (296 kg/m^3)				
4 (0.10)	*	*	*	*
8 (0.20)	*	*	*	*
12 (0.31)	48 (9)	44 (7)	40 (4)	36 (2)
18 (0.46)	36 (2)	22 (–6)	8 (–13)	–6 (–21)
24 (0.61)	28 (–2)	6 (–14)	–16 (–27)	–38 (–39)
30 (0.76)	22 (–6)	–7 (–22)	–36 (–38)	–64 (–53)
36 (0.91)	16 (–9)	–18 (–28)	–50 (–46)	†
Cement content = 600 lb/yd^3 (356 kg/m^3)				
4 (0.10)	*	*	*	*
8 (0.20)	*	*	*	*
12 (0.31)	44 (7)	38 (3)	32 (0)	26 (–3)
18 (0.46)	31 (–1)	14 (–10)	–5 (–21)	–24 (–31)
24 (0.61)	22 (–6)	–5 (–21)	–32 (–36)	–61 (–52)
30 (0.76)	14 (–10)	–19 (–28)	–67 (–55)	†
36 (0.91)	7 (–14)	–30 (–34)	†	†

* > 50°F (10°C): additional heat required.

† << –60°F (–51°C).

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 requirements given in the tables and figures by approximately 30%. Where other types of cements or blends of cement and other

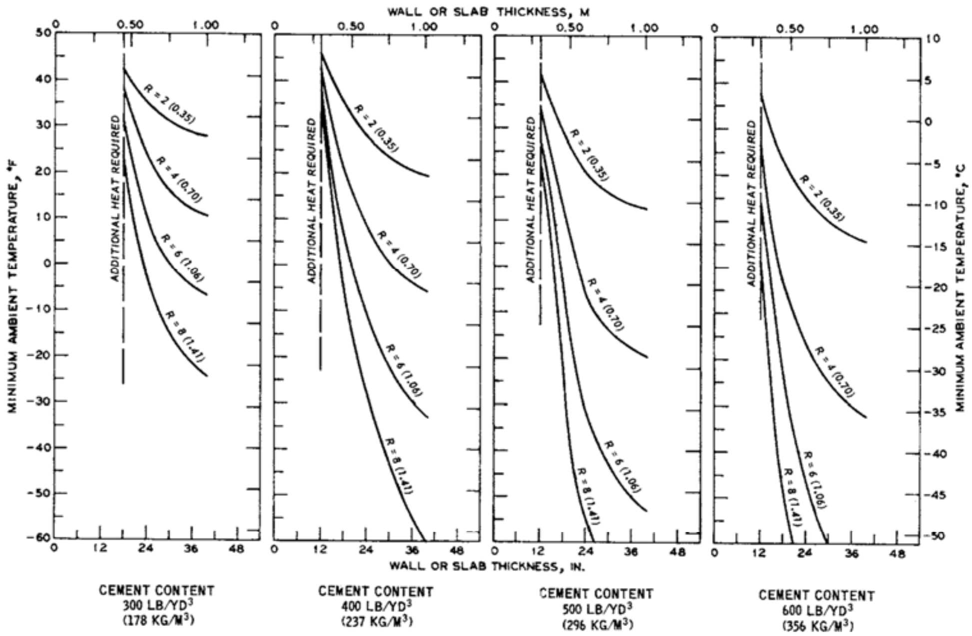

Fig. 9.4—Minimum exposure temperatures for concrete flatwork placed on ground as a function of member thickness, R*-value, and cement content. Concrete placed and surface temperature maintained at 50°F (10°C) for 3 days on ground at 35°F (2°C).*

Table 9.4—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)

Slab thickness, in. (m)	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			
	R = 2 (0.35)	*R* = 4 (0.70)	*R* = 6 (1.06)	*R* = 8 (1.41)
Cement content = 300 lb/yd³ (178 kg/m³)				
4 (0.10)	*	*	*	*
8 (0.20)	*	*	*	*
12 (0.31)	*	*	*	*
18 (0.46)	42 (6)	38 (3)	32 (0)	26 (–3)
24 (0.61)	37 (3)	25 (–4)	11 (–12)	–3 (–19)
30 (0.76)	31 (–1)	15 (–9)	–1 (–18)	–17 (–27)
36 (0.91)	31 (–1)	12 (–11)	–5 (–21)	–22 (–30)
Cement content = 400 lb/yd³ (237 kg/m³)				
4 (0.10)	*	*	*	*
8 (0.20)	*	*	*	*
12 (0.31)	46 (8)	44 (7)	42 (6)	40 (4)
18 (0.46)	36 (2)	22 (–6)	8 (–13)	–6 (–21)
24 (0.61)	28 (–2)	9 (–13)	–10 (–23)	–29 (–34)
30 (0.76)	21 (–6)	0 (–18)	–21 (–29)	–42 (–41)
36 (0.91)	21 (–6)	–4 (–20)	–29 (–34)	–50 (–46)
Cement content = 500 lb/yd³ (296 kg/m³)				
4 (0.10)	*	*	*	*
8 (0.20)	*	*	*	*
12 (0.31)	42 (6)	36 (2)	30 (–1)	24 (–4)
18 (0.46)	30 (–1)	12 (–11)	–6 (–21)	–22 (–30)
24 (0.61)	21 (–6)	–5 (–21)	–31 (–35)	–50 (–46)
30 (0.76)	16 (–9)	–10 (–23)	–42 (–41)	–74 (–59)
36 (0.91)	16 (–9)	–18 (–28)	–50 (–46)	†
Cement content = 600 lb/yd³ (356 kg/m³)				
4 (0.10)	*	*	*	*
8 (0.20)	*	*	*	*
12 (0.31)	38 (3)	26 (–3)	14 (–10)	2 (–17)
18 (0.46)	24 (–4)	0 (–18)	–24 (–31)	–48 (–44)
24 (0.61)	14 (–10)	–16 (–27)	–46 (–43)	–82 (–63)
30 (0.76)	10 (–12)	–20 (–29)	–62 (–52)	†
36 (0.91)	7 (–14)	–30 (–34)	†	†

* > 50°F (10°C): additional heat required.
† << –60°F (–51°C).

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. Insulation beyond the required amount should not be used because it may 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 required thickness 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/yd^3 (296 kg/m^3). There will be no early-age strength requirements for the concrete; as per Table 5.1, therefore, a 3-day protection period will be used. The forms are made of 3/4 in. (20 mm) plywood. The contractor would like to use plain expanded polystyrene boards for insulation. What should be the thickness of the polystyrene boards?

Solution—Solve the problem by using Table 9.2 or Fig. 9.2. According to Table 9.2, an *R*-value of 4 (0.7) is sufficient for an ambient temperature of 2°F (–16°C), which will be assumed to be close enough to the expected ambient temperature. Because the plywood forms will provide some of this insulation, the required added insulation should have an *R*-value of 4 – 0.94 = 3.06 (0.70 – 0.17 = 0.53). Referencing Table 9.2, a 1 in. (25 mm) plain polystyrene board has an *R*-value of 4 (0.7). Therefore, 3/4 in. (20 mm) thick polystyrene boards (4 × 3/4 = 3, which is approximately 3.06), will provide the needed additional insulation.

9.4—Selection of insulation for use with hydronic heaters

Hydronic heaters deliver supplemental heat to the protected concrete surface or to the non-working side of the forms. The role of insulation is to retain a reasonable portion of the supplemental heat being delivered and to retard the escape of heat of hydration. Unlike Section 9.3 where no supplemental heat is available, the insulation in this instance is not as important so it need not be finely tuned to offset ambient weather conditions. Use insulating materials as described in Section 9.2 that have an *R*-value rating of 4 to 6. Refer to Table 9.2 for the number of layers of insulation to achieve this value.

9.5—Heaters

9.5.1 *Introduction*—Three types of heaters are commonly available for use in cold weather concreting: direct fired, indirect fired, and hydronic heating systems. Direct fired and indirect fired heaters discharge hot air into an enclosed space. Hydronic heaters circulate a heated glycol/water heat transfer fluid (liquid) through a system of heat transfer hoses placed on the surface. Heat conducts from the heat transfer hoses directly to the concrete form or substrate. Insulation blankets cover the hoses to confine the heat.

9.5.2 *Direct fired heaters*—Direct fired heaters are simple, relatively inexpensive devices that produce hot air. The more sophisticated models have a fan to circulate the hot air. A small (less than 400,000 BTU [400 MJ]) direct fired heater with or without a fan is also called a salamander or a torpedo heater. Direct fired heaters typically burn fuel oil, kerosene, propane, gasoline, or natural gas. Combustion of these fossil fuels produces a large amount of CO_2 and, to a lesser extent, carbon monoxide (CO). Direct fired heaters discharge these products into the enclosed air space being heated, and 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 ($CaCO_3$) (Kauer and Freeman 1955). This $CaCO_3$ 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.

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: the exhaust is separate from the hot air, vented outdoors, and 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.

Table 9.5—Thermal resistance of various insulating materials

Insulating material	Thermal resistance *R* for these thicknesses of material*	
	1 in., h·ft^2·°F/BTU	10 mm, m^2·K/W
Boards and slabs		
Expanded polyurethane (*R*-11 exp.)	6.25	0.438
Expanded polystyrene extruded (*R*-12 exp.)	5.00	0.347
Expanded polystyrene extruded, plain	4.00	0.277
Glass fiber, organic bonded	4.00	0.277
Expanded polystyrene, molded beads	3.57	0.247
Mineral fiber with resin binder	3.46	0.239
Mineral fiber board, wet felted	2.94	0.204
Sheathing, regular density	2.63	0.182
Cellular glass	2.63	0.182
Laminated paperboard	2.00	0.139
Particle board (low-density)	1.85	0.128
Plywood	1.25	0.087
Blanket		
Mineral fiber, fibrous form processed from rock, slag, or glass	3.23	0.224
Loose fill		
Wood fiber, soft woods	3.33	0.231
Mineral fiber (rock, slag, or glass)	2.50	0.173
Perlite (expanded)	2.70	0.187
Vermiculite (exfoliated)	2.20	0.152
Sawdust or shavings	2.22	0.154

*Values from *ASHRAE Handbook of Fundamentals*, 1977, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, New York.

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 Section 9.2. The number of layers should be determined by using Table 9.2. Hydronic heaters can be used outdoors to thaw or preheat subgrades before concrete placement. They are also used to provide supplementary heat to cure 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 fume-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

Enclosures may be the most effective means of protection, but they are also 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 required for placing operations when the air temperature is lower than –5°F (–20°C). Builders attempting to place concrete at such low temperatures without enclosures encounter manpower and equipment difficulties that result in inferior construction.

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 required 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 Sections 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 required 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 actions can be taken to adjust temperatures if they drift outside the recommended ranges. Electronic data loggers should be employed to automatically poll 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 maturity method, Section 8.4). Historical temperature data should be retained as a part of the engineering 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°C) below the minimum value in Table 5.1, the deficiency in protection would be 90°F-hour (48°C-hour). Therefore, extend the protection period for 180°F-hour (96°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 REQUIREMENTS AND METHODS

10.1—Introduction

Newly placed concrete should be protected from drying so that adequate hydration can occur. Measures should be taken to prevent evaporation of moisture from concrete. During cold weather, when the air temperature is below 50°F (10°C), atmospheric conditions in most areas will not cause excessive drying. However, new concrete is vulnerable to freezing when it is in a critically saturated condition. Therefore, if concrete has been saturated during the protection period, it should be allowed to undergo some drying before being exposed to freezing temperatures.

10.2—Curing during the protection period

Concrete exposed to cold weather is unlikely to dry at an undesirable rate, but this may not be 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 (particularly finished floors), however, 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 prevent drying. The preferred technique is to use steam for heating and preventing excessive evaporation. 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 because during subfreezing periods it produces icing problems where water escapes the enclosure or where there is a poor seal. It also increases the likelihood of the concrete freezing 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 before and during the gradual adjustment to ambient cold weather conditions, as discussed in Section 7.4.

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%. During very cold weather, it is always necessary to add moisture to heated air to maintain this humidity. For example, if the outside temperature is 10°F (–12°C), the relative humidity of the air within the heated enclosure will be less than 20% if no moisture is added.

10.3—Curing following the protection period

Following removal of the temperature protection, it is usually unnecessary to provide measures to prevent excessive drying as long as the air temperature remains below 50°F (10°C), except when placing concrete in extremely arid regions. Applying a curing compound during the first period of above-freezing temperature after protection removal eliminates the need to conduct further curing operations when the temperature rises above 50°F (10°C).

The severity of drying depends on four factors:

- The temperature of the concrete;
- The temperature of the air;
- The wind speed; and
- The relative humidity of the air.

For example, excessive drying occurs when concrete at 50°F (20°C) is exposed to an air temperature of 50°F (10°C) and a relative humidity less than 40%. As the air temperature decreases, the air requires a higher relative humidity to prevent excessive drying. For example, when concrete at 50°F (10°C) is exposed to air having a temperature of 40°F (5°C), the air should have a relative humidity greater than 60% to prevent excessive drying. However, when the concrete temperature drops to 40°F (5°C), an ambient air temperature of 40°F (5°C) with a relative humidity of 11% can be tolerated. For air temperatures above 50°F (10°C), the rate of drying increases rapidly.

When excessive drying is anticipated and no freezing is expected, concrete may be water cured. Otherwise, the use of curing compounds or an impervious cover is preferred. During cold weather periods when freezing occurs, occasional peak temperatures above 50°F (10°C) should not be a concern. However, when temperatures above 50°F (10°C) occur during more than half of any 24-hour period for 3 consecutive days, the concrete should no longer be regarded as cold weather concrete and normal curing practice should apply (ACI 308R).

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 achieve setting and required strength. The reduction in setting time and the acceleration of strength gain often result in savings due to a shorter protection period, faster reuse of forms, earlier removal of shores, or less labor in finishing flatwork. 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 carefully evaluated. For more information on evaluation of thermal gradients in mass concrete, refer to ACI 207.1R.

Materials or methods used to obtain high-early-strength concrete increase the heat of hydration, which can be favorable in some instances. When resistance to sulfate attack is not a concern, cement having higher percentages of tricalcium silicate and tricalcium aluminate may be advantageous in cold weather because these compounds contribute to earlier strength development and higher heat of hydration. Cements of the same type and brand can have wide variations in setting times and rates of strength development. To show which alternative produces the desired properties, testing the concrete made with the cements to be used for a particular job is recommended. If additional cement is considered, trial mixtures using the increased cement factor should be tested because the accelerated strength development varies with each cement and temperature exposure. 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 setting and strength development is available in ACI 212.3R. Accelerating admixtures can be classified into four categories (Scanlon and Ryan 1989):

- Calcium chloride;
- Accelerating admixtures containing $CaCl_2$;
- Non-chloride accelerating admixtures; and
- Non-chloride accelerating admixtures for use in concrete exposed to sub-freezing ambient temperatures.

Developments in chemical admixture technology are making it possible to place fresh concrete in cold weather without thermal protection. In 1994, the U.S. Army Corps of Engineers Construction Productivity Advancement Research program (Korhonen and Brook 1996) produced two prototype low-temperature (antifreeze) admixtures. Each of these mixtures depressed the freezing point of the mixing water and accelerated the hydration of cement to allow concrete held at an internal temperature of 23°F (–5°C) immediately after mixing to gain strength as rapidly as control concrete held at 41°F (5°C). Field studies showed that the added cost of placing concrete protected with these admixtures was roughly 1/3 less than control concrete protected with heated enclosures. Commercial acceptance of this technology has been slow to develop mostly because there are no acceptance standards for antifreeze admixtures, and practitioners are reluctant to place concrete in sub-freezing ambient temperatures. For antifreeze admixture technology to become readily available, standards should be written and supported by technology demonstration. ASTM began developing a specification for antifreeze admixtures in 2003. The technology was demonstrated by the U.S. Army Corps of Engineers in a 3-year study with 10 northern Departments of Transportation. This study developed a protocol for using off-the-shelf admixtures in low-temperature concreting applications (Korhonen 2002). The U.S. Army Corps of Engineers northern state alliance ended in 2003. Refer to Section 11.2.6 for further discussion of antifreeze admixtures.

11.2—Accelerating admixtures

11.2.1 *General*—Accelerating admixtures are widely used for cold weather concreting practices. Accelerators increase the rate of reaction between cement and water. This effect is used to offset the reduction in reaction rate due to lower temperatures, or can be used to increase internal concrete temperature. While reducing setting time and increasing rate of strength gain, these admixtures do not significantly lower the freezing point of water in concrete. Some chemicals have been used to depress the freezing point of water in fresh concrete (Korhonen 1990) and when used in conjunction with accelerators interesting results have been achieved (Section 11.2.6). However, because there are insufficient data on the long-term performance of concrete mixtures made with these chemicals, their use is not recommended until technology demonstrations have been conducted and new standards developed.

11.2.2 *Calcium chloride*—Calcium chloride is a widely used accelerating admixture that reduces setting time and increases the rate of early-age strength development of concrete. The use and effects of $CaCl_2$ are discussed in ACI 212.3R, ACI 201.2R, and Shideler (1952). ACI 318 prescribes the maximum chloride ion content of concrete, and these limits govern concrete used in any structures designed under the provisions of that document. In general, $CaCl_2$, or any other chloride-bearing admixture, should not be used in concrete containing reinforcing steel. Calcium chloride added to the concrete mixture in permissible quantities will not significantly lower the freezing point of water in concrete. To avoid misplaced confidence in such a practice, and to avoid use of harmful materials, any attempt to lower the freezing point of the water in concrete by the use of $CaCl_2$ should not be permitted.

11.2.3 *Accelerating admixtures containing $CaCl_2$*—Some water-reducing accelerating admixtures, conforming to Type E in ASTM C494/C494M, accelerate setting and strength gain at ambient temperatures of 50°F (10°C) and below, and reduce the required water content of the mixture. Many Type E admixtures usually contain less than 0.25% $CaCl_2$ by mass of the cementitious materials when used at recommended dosage rates. The accelerating performance of these admixtures may be primarily due to the $CaCl_2$ or from blending with other accelerating ingredients (Korhonen 1990). Type E chemical admixtures reduce setting times and significantly improve strength gain at 24 hours. The set time and early-age strength of concrete containing these multi-component admixtures approaches or equals the performance obtained by using 2% $CaCl_2$, but at a lower level of $CaCl_2$ addition. These admixtures provide early-age strengths appreciably greater than some concrete made with Type III cements.

11.2.4 *Non-chloride accelerating admixtures*—Where $CaCl_2$ presents durability problems, using non-chloride admixtures may be appropriate. The user should obtain data from the manufacturer to verify the admixture's effect on fresh and hardened concrete properties. The term "non-chloride" does not indicate that the admixture is 100% chloride free. Typically, the non-chloride certification issued by the manufacturer says the admixture contains no more than 0.05% chloride ions by mass, that is, no more than 500 parts per million. Specifying a non-chloride accelerator doesn't guarantee the accelerator will be noncorrosive. Consult the manufacturer to obtain long-term data indicating that the product is noncorrosive.

11.2.5 *Non-chloride accelerating admixtures for use in sub-freezing ambient temperatures*—Non-chloride admixtures are available that allow concrete to set, gain strength, and be protected from freezing when exposed to ambient temperatures as low as 20°F (–7°C). These admixtures are a combination of non-chloride accelerator and water-reducer that meet requirements of ASTM C494/C494M for Type C, accelerating admixtures and Type E, or both, water-reducing and accelerating admixtures. As with $CaCl_2$, these non-chloride admixtures, used at their recommended dosage rates, do not significantly reduce the freezing point of water in concrete.

These admixtures greatly accelerate the early heat of hydration and decrease the water-cementitious material ratio (*w/cm*). These admixtures increase the rate of internal heat generation to maintain a temperature sufficient to sustain continued hydration despite ambient temperatures as low as 20°F (–7°C). Admixture dosages that allow the concrete to achieve initial set in 5 to 6 hours at an ambient temperature of 20°F (–7°C) generally range from 2% to 4% solids of admixture per mass of cement or cementitious materials. Smaller dosages will not provide protection against freezing when exposed to an air temperature of 20°F (–7°C), but can be effective accelerators at higher ambient temperatures. Concrete mixtures containing these admixtures and placed at an initial temperature in accordance with Table 7.1 achieve satisfactory strength and durability at an ambient temperature of 20°F (–7°C) without any thermal protection, provided there is no external supply of water (Brook et al. 1988; Brook and Ryan 1989; Grogan 1990). The use of high-quality curing compound may eliminate problems due to an external water supply. There is however, a potential for concrete damage or slow strength gain when the ambient temperature drops below 20°F (–7°C). Contractors should consider this possibility and be prepared for changes in ambient temperature during placing and curing. Wind breaks or insulating blankets, or both, may be required to retain heat generated within the concrete to offset a temperature decrease or wind speed increase.

11.2.6 *Antifreeze admixtures*

11.2.6.1 *Background*—The use of antifreeze admixtures dates to the 1950s when Soviet scientists (Korhonen 1990) reported early success in chemically depressing the freezing point of concrete mixing water. The first commercial interest in antifreeze admixtures in the United States occurred in 1992, when the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) partnered with private industry to produce two prototype antifreeze admixtures that protected concrete down to 23°F (–5°C) (concrete temperature) (Korhonen and Brook 1996; Korhonen et al. 1997). The prototype admixtures were not commercialized, primarily because it was felt that an industry standard should be in place before this technology could be opened to general practice.

The U.S. Army Corps of Engineers studied antifreeze admixtures through the mid-1990s. In 1997, CRREL designed an antifreeze admixture from commercial, off-the-shelf chemicals for use by the Tennessee Valley Authority inside the ice condenser room of one of its nuclear power plants. This study shows it is possible to design and specify antifreeze admixtures from conventional materials without requiring special acceptance standards (Korhonen 2002).

For the Department of Defense (DOD) (Korhonen and Brook 1996), it became increasingly clear that there are times when concrete should be placed regardless of the weather, and that insulation or heated enclosures might not be available. This situation presented a problem and an opportunity. The problem was placing unprotected concrete when it could be damaged by the cold. The opportunity was that in contingency operations on the battlefield or in other emergency situations, long-term performance may not be a consideration and acceptance standards would not be important. This allowed examination of a wider scope of chemicals than might otherwise be acceptable for commercial application. In 1999, CRREL evaluated various materials for use as expedient concrete admixtures and published a report for the Army on concrete not expected to last more than 5 years (Korhonen 1999).

Because using chemicals to protect concrete against freezing has proven technically feasible but is still not practiced in the United States, CRREL worked with the Federal Highway Administration (FHWA) to develop antifreeze admixtures from those that are used for various purposes in concrete (Korhonen 2002). This was done to avoid the necessity of developing a new acceptance standard. It was previously shown that cold weather admixtures could be formulated by combining existing admixtures, which already comply with industry practice. The goal was to not use more of any single admixture than recommended by its manufacturer, but to use sufficient numbers of admixtures so concrete can safely resist freezing down to 23°F (–5°C). The admixture combination should also force the concrete when it is cold to cure as rapidly as control concrete cured at 40°F (5°C). The initial setting of cold concrete was established to be not longer than that of control concrete cured at 40°F (5°C). This program, started in April 2001, was scheduled to run for 3 years. It was funded by a consortium of northern DOTs and was monitored by the FHA.

In 2003, Committee ASTM C09.23.03 on Chemical Admixtures decided to begin drafting a specification for antifreeze admixtures.

11.2.6.2 *Composition*—As a minimum, an antifreeze admixture should contain chemicals that depress the freezing point of water, as well as chemicals that accelerate the hydration of cement. There are numerous chemicals that accelerate cement hydration, such as $CaCl_2$, calcium nitrite [$Ca(NO_3)$], sodium thiocyanate (NaSCN), potassium carbonate (K_2CO_3), and calcium formate [$Ca(HCOO)_2$]. Practically anything that dissolves in water can be a freezing point depressant. The challenge is to select chemicals that work together and do not harm the concrete, steel reinforcement, or the environment.

11.2.6.3 *Strength*—Temperature affects the rate concrete develops strength. In general, low temperatures retard the rate at which normal concrete gains strength, whereas high temperatures accelerate it. When cured at 23°F

(–5°C), a concrete made with an antifreeze admixture can gain strength as rapidly as control concrete cured at 40°F (5°C). The ultimate strength of antifreeze concrete cured at low temperatures may be comparable to or greater than that of normal concrete cured at room temperatures.

11.2.6.4 *Freezing and thawing resistance*—When tested according to ASTM C666/C666M, Procedures A and B, concrete made with various antifreeze chemicals is as durable as the control concrete, when properly entrained with air. Durability factors of 96 at the end of 300 cycles of freezing and thawing have been reported for concrete made with antifreeze admixtures compared with durability factors of 99 for control concrete (Korhonen and Brook 1996). Microscopic examination showed that the entrained air void system in hardened concrete was unaffected by antifreeze admixtures. Thus, the antifreeze admixtures evaluated so far do not appear to reduce the freezing and thawing resistance of concrete.

11.2.6.5 *Reactive aggregates*—Antifreeze admixtures do not necessarily increase the alkali content of the concrete. However, if antifreeze admixtures contain alkali metals, the alkali ions that dissociate into the mixing water will raise the pH of the pore fluid and could contribute to an alkali-silica reaction with certain siliceous aggregate.

11.2.6.6 *Corrosion*—Antifreeze admixtures made from nonchloride chemicals have shown no tendency to corrode embedded reinforcing steel. Chemicals such as sodium nitrite ($NaNO_3$) and $Ca(NO_3)$ inhibit corrosion when used according to the manufacturer's recommendations.

11.2.6.7 *Batching*—Usually, chemical admixtures are delivered in liquid form and the same should be expected for antifreeze admixtures. Though most admixtures are dispensed at the concrete plant, it may be advantageous to add antifreeze admixtures into the concrete at the construction site, especially if the admixture contains mostly accelerating compounds. As with other admixtures, antifreeze admixtures be added separately into the mixture and not be mixed with other admixtures.

11.2.6.8 *Cost benefits*—Antifreeze admixtures can be cost-effective. The cost of conventional concreting in cold weather can be 100% or more than that done under summertime conditions. The winter surcharge is the result of increased equipment, labor, and energy costs. Antifreeze admixtures are economically competitive with the higher prices associated with conventional cold weather concreting practice between 23 and 40°F (–5 and 5°C), as well as lengthening the winter concreting season by several months.

11.2.7 *Summary*—If adequate information or past performance records are unavailable, test to evaluate the effect of a particular admixture or admixtures on the concrete for the job. Perform these tests at the expected job temperatures using the materials approved for the job. Verify the accelerated setting and strength development properties claimed by manufacturers of proprietary admixtures. If the admixture under consideration contains chloride, determine the chloride percentage, by mass of cement, introduced into the concrete if the admixture were used and compared with the permissible limits given in ACI 318. The admixture should not be used if the limits are exceeded.

11.3—Rapid-setting cements

Some modified portland cements and 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 (11.7 MPa) to more than 8000 psi (55.2 MPa). Generally, these cements have been used for concrete repairs or other special applications, but not for general concrete construction. Rapid-setting cements are typically proprietary products and the performance of concrete incorporating these cements should be evaluated using job materials and under job conditions. One study of a rapid-setting cement found major differences in the chemical composition between different shipments (Houston and Hoff 1981). No standard purchase specification exists for rapid-setting cements, although ASTM C928/C928M covers packaged products.

CHAPTER 12—REFERENCES

12.1—Referenced standards and reports

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

American Concrete Institute

201.2R Guide to Durable Concrete
207.1R Guide to Mass Concrete
207.4R Cooling and Insulating Systems for Mass Concrete
212.3R Chemical Admixtures for Concrete
228.1R In-Place Methods to Estimate Concrete Strength
301 Specifications for Structural Concrete
302.1R Guide for Concrete Floor and Slab Construction
306.1 Standard Specification for Cold Weather Concreting
308R Guide to Curing Concrete
318 Building Code Requirements for Structural Concrete and Commentary
347.2R Guide for Shoring/Reshoring of Concrete Multi-story Buildings

ASTM International

C31/C31M Standard Practice for Making and Curing Concrete Test Specimens in the Field
C150/C150M Standard Specification for Portland Cement
C309 Standard Specification for Liquid Membrane-Forming Compounds for Curing Concrete
C494/C494M Standard Specification for Chemical Admixtures for Concrete
C595/C595M Standard Specification for Blended Hydraulic Cements
C597 Standard Test Method for Pulse Velocity Through Concrete

C666/C666M	Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing
C684	Standard Test Method for Making, Accelerated Curing, and Testing Concrete Compression Test Specimens
C803/803M	Standard Test Method for Penetration Resistance of Hardened Concrete
C805/C805M	Standard Test Method for Rebound Number of Hardened Concrete
C873/C873M	Standard Test Method for Compressive Strength of Concrete Cylinders Cast in Place in Cylindrical Molds
C900	Standard Test Method for Pullout Strength of Hardened Concrete
C918/C918M	Standard Test Method for Measuring Early-Age Compressive Strength and Projecting Later-Age Strength
C928/C928M	Standard Specification for Packaged, Dry, Rapid-Hardening Cementitious Materials for Concrete Repairs
C1064/C1064M	Standard Test Method for Temperature of Freshly Mixed Hydraulic-Cement Concrete
C1074	Standard Practice for Estimating Concrete Strength by the Maturity Method
C1157/C1157M	Standard Performance Specification for Hydraulic Cement

Portland Cement Association

IS128	Concrete for Massive Structures

These publications may be obtained from these organizations:

American Concrete Institute
38800 Country Club Drive
Farmington Hills, MI 488331
www.concrete.org

ASTM International
100 Barr Harbor Drive
West Conshohocken, PA 19428
www.astm.org

Portland Cement Association
5420 Old Orchard Road
Skokie, IL 60077
www.cement.org

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