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ACI 306R-16

Guide to Cold Weather Concreting

Reported by ACI Committee 306

William J. Lyons III, Chair

Kevin A. MacDonald, Vice Chair

Kim D. Basham James R. Baty II Michael Patrick Berry Charles D. Binkowski Ken Cannella Terry C. Collins

Terry L. Lavy

Robert J. Ryan

D. Gene Daniel David J. Elmer Mario Garza John P. Gnaedinger Robert J. Hoopes Kenneth C. Hover Eric D. King Ronald L. Kozikowski Jr. Steve R. Lloyd Sr. Michael J. Marchese Stephen C. Morrical Craig M. Newtson

Consulting Members

Harold B. Wenzel Sixin Yang Victor I. Subkov

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

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

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William D. Palmer Jr. Dennis R. Purinton Domenick Thomas Ruttura Valery Tokar

Erik Holck, Secretary

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CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Introduction

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

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

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

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

1.2—Scope

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

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

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation M = maturity factor, deg-h



- t_a = ambient air temperature, °F (°C)
- t_r = concrete temperature upon delivery to the jobsite, °F (°C)
- $T = \text{concrete temperature, } ^{\circ}\text{F}(^{\circ}\text{C})$
- T_a = coarse aggregate temperature, °F (°C)
- T_c = cement temperature, °F (°C)
- T_d = drop in temperature to be expected during a 1-hour delivery time, °F (°C). (This value should be added to t_r to determine the recommended temperature of concrete at the plant after batching.)
- $T_o = \text{datum temperature, } ^\circ F (^\circ C)$
- T_s = fine aggregate temperature, °F (°C)
- T_w = temperature of added mixing water, °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)
- $\Delta t =$ duration of curing period at concrete temperature *T*, deg-h

2.2—Definitions

ACI provides a comprehensive list of definitions through an online resource, "ACI Concrete Terminology," https:// www.concrete.org/store/productdetail.aspx?ItemID=CT16. Definitions provided herein complement that resource.

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

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

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

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

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

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

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



Table 7.2—Length of protection period for concrete placed during cold weather

induced (Protection period at minimum temperature indicated in Line 1 of Table 5.1, days*			
Line	Service condition	Normal-set concrete	Accelerated-set concrete		
1	No load, not exposed	2	ano di 1erential		
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.

CHAPTER 8—PROTECTION AGAINST FREEZING 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 form soffits and shores, provide protection time beyond the minimums given in Table 7.2, 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 recommendations given in 8.10.

8.2—Field-cured cylinders

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

8.3—In-place testing

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

8.4—Maturity testing

Concrete maturity is based on the concept that the combination of curing time and temperature of the concrete yields a specific strength for a given concrete mixture. There are a number of ASTM test methods that deal with maturity testing (ASTM C918/C918; ASTM C1074). The maturity concept as originally defined by Saul (1951) considers the relationship of time, temperature, and strength gain. The





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

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

will affect the maturity relationship.

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

$$M = \sum (T - T_o)\Delta t \tag{8.4}$$

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

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

Strength prediction based on the maturity index assumes the in-place concrete has the same strength potential as the concrete used to develop the strength-maturity relationship. Before removing forms, soffits, or shores, it is necessary to determine whether the in-place concrete has attained the



Fig. 8.4—Maturity meter suspended from structure.

target strength by validating the strength determined from the strength-maturity relationship by performing additional tests such as:

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

(b) Early-age strength test of standard-cured cylinders fitted with maturity data loggers (ASTM C1074)

i. Determine the compressive strength of the test cylinders in accordance with ASTM C39/C39M.

ii. Compare the compressive strength of the cylinders with the established strength-maturity relationship.

iii. If these differ by more than 10 percent, a new strengthmaturity relationship is needed, and another test is needed to determine the in-place strength of the concrete.

(c) Cylinders cast in-place in cylindrical molds in accordance with ASTM C873/C873M

(d) Penetration resistance test in accordance with ASTM C803/803M

(e) Pullout test in accordance with ASTM C900

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

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



1	2	3		4		5		6	7		8		9	
	Elapsed time	ed Temperature in structure		Average temperature in structure, T		Column 4 – T _o *		Time interval	$\begin{array}{c c} (T-T_o)\Delta t\\ Column 5 \times\\ Column 6 \end{array}$		Maturity index M ∑ Column 7		Corresponding compressive strength	
Date	h , h	°F	°C	°F	°C	°F	°C	Δt , h	°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

Table 8.4.1—Calculation of maturity index and estimated in-place strength

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





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

8.5—Attainment of design strength

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



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

8.6—Increasing early strength

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

(a) Initial temperature of the concrete when placed

(b) Temperature at which the concrete is maintained

(c) Type, amount, and properties of the cementitious materials

(d) *w/cm*

(e) Type and dose of accelerating and other admixtures used

(f) Conditions of protection and curing

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

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

(b) Using types and compositions of cement that exhibit higher early strength development and using higher cement content with a lower w/cm (11.1)

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

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

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

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

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

8.7—Cooling concrete

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

8.8—Estimating strength development

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

8.9—Removal of forms and supports

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



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

Table 8.8—Duration of	f recommended pi	otection
for percentage of stan	dard-cured 28-day	y strength

Percentage	At 50	°F (10°C)	, days	At 70°F (21°C), days				
of standard- cured	Ty	pe of cem	ent	Type of cement				
28-day strength	I	п	ш	I	П	ш		
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 $70 \pm 3^{\circ}$ F (21 \pm 1.7°C), and did not contain fly ash. The 28-day strength for each type of cement was considered as 100 percent in determining the times to reach various percentages of this strength for curing at 50 and 70° F (10 and 21°C). These times are only approximate, and specific values should be obtained for the concrete used on the job.

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

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

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

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

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

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

8.10—Estimating strength development: modeling cold weather placements

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

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

Two assumptions commonly used during modeling are:

(1) Early-age concrete hydration is negligible below a concrete temperature of 40° F (5°C)

(2) Freezing damage may take place when the concrete temperature drops below $32^{\circ}F(0^{\circ}C)$

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

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

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

The temperature of concrete placed during cold weather should be maintained at the recommended temperature given in Line 1 of Table 2.2, or until the in-place strongth has recommended in Table 2.2, or until the in-place strongth has reached the level specified by the Ticorset decige protectional to terminate protection. The specific protection system needed to maintain the recommended temperatures depends on factors such as anti-concrete mother conditions, and the structure, and concrete mother protection is not factors such as anti-concrete mother protection the needed to maintain the recommended temperatures depends on factors such as anti-concrete mother protections 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 temperatures levels. It is necessary to maintain the recommended temperatures and use the natural heat of hydration to maintain the recommended temperatures levels. It is necessary to build enclosures and use heaters to maintain the recommended temperatures levels incore instances, hydromic heaters and insulation blankets are adequate to maintain concrete placements within the propertione formers and insulation blankets are adequate to maintain concrete placements within the properPolystyrene foun sheets: Sheets can be cat to shape wedged between the study of the forms or glued into place edged between the study of the forms or glued into place (1) Urethams found: Boam may be speayed onto this ace of forms, making a continuous insulating layer of forms, making a continuous insulating layer discussion resistant ensured should be sprayed over hane form to reduce water absorption and protect it from while tays. Use prethance form with contion because its

> and higher performing blankets incorporate for the second second

Selection of Insulation when supplementary when supplementary

Construite demperature records neveral the effectiveness of different amounts or types of mathation and of other protection methods for various types of construct 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

As mentioned in 9.2, the heat of hydration is high during this first 3 days after placement and then gradually decreases. If maintain a specified temperature throughout the protection period, the amount of recommended insulation is greater for a large period.