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ACI 306R-10

Guide to Cold Weather Concreting

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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.

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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

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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, electrochemical, 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.

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.

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 accordance 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-l) to sum the successive products of the time intervals and the corresponding average concrete temperature above the datum temperature.

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

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.

Fig. 8.1—Maturity meter.

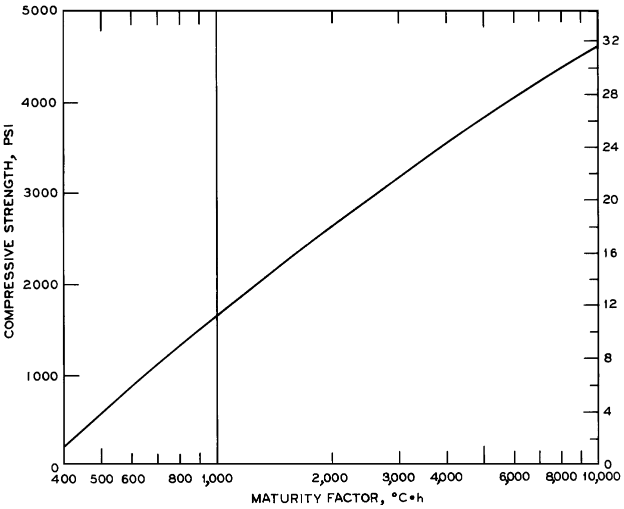

Fig. 8.2—Example of a strength-maturity factor relationship for laboratory-cured cylinders (73°F [22.8°C]).

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

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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).

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.

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.

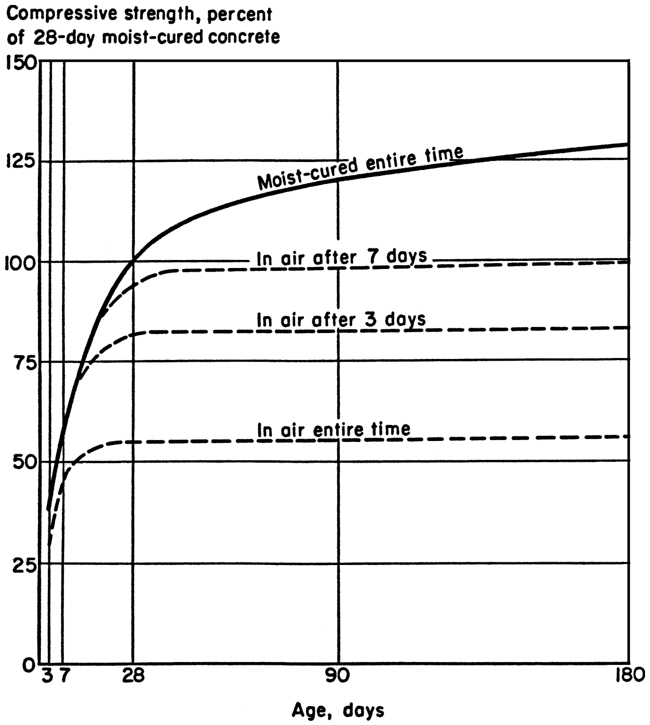

Fig. 8.3—Compressive strength of concrete dried in laboratory air after preliminary moist curing (Price 1951).

8.6—Increasing early strength

Many factors influence the time needed for concrete to attain the strength 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 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

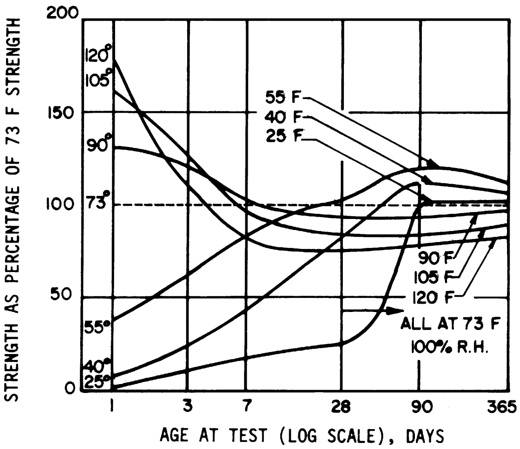

Fig. 8.4—Effect of temperature conditions on the strength development of concrete (Type I cement) (Kleiger 1958).

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;

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.

- 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.

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.

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