Cold Weather Concreting Strategies

Choosing sustainable cold weather protection

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It's been estimated that the costs associated with cold weather concrete construction (for example, providing heated enclosures) can exceed the cost of ready mixed concrete alone.[1] This article provides a review of cold weather concreting practices and their effects on construction costs and quality, and proposes strategies for cold weather protection based on principles and concrete contractor experiences.

ACI Requirements and Recommendations

Contractors placing concrete on or against cold surfaces are often directed to three ACI documents: "Specifications for Structural Concrete (ACI 301-10),"[2] "Standard Specification for Cold Weather Concreting (ACI 306.1-90),"[3] and "Guide to Cold Weather Concreting (ACI 306R-10)."[4] But the cold weather concreting strategies provided in these documents have significant differences.

ACI 301 and ACI 306.1 are written in mandatory language and thus provide requirements when cited in project specifications. Section 5.3.2.1b of the 2010 edition of ACI 301[2] states: "Unless otherwise permitted, do not place concrete in contact with surfaces less than 35°F [1.7°C]." This requirement was not in the 2005 edition of ACI 301, and there is no similar requirement in the 1990 edition of ACI 306.1.[3]

ACI 306R-10[4], Section 6.1, states that: "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." These two sentences comprise two significantly different recommendations for surfaces that will come into contact with fresh concrete. While the first indicates that surfaces should be above 32°F (0°C)—slightly less than the ACI 301-10[2] requirement of 35°F (1.7°C)—the second imposes a temperature envelope based on the concrete temperature (this can be significantly higher than the ACI 301 requirement).

Table 5.1 of ACI 306R-10[4] provides recommended minimum as-placed concrete temperatures. For concrete sections less than 12 in. (305 mm) thick, for example, the recommended concrete temperature is 55°F (13°C). Thus, the surface temperature envelope would range from 40 to 65°F (5 to 18°C). Although ACI 306R is an ACI Guide and is not supposed to be referenced in project specifications, it often is. As a result, some inspectors attempt to enforce the recommendations, with potentially costly effects. For example, it's conceivable that an inspector could require a contractor to increase the minimum surface temperature from 40 to 45°F (4 to 7°C) if the concrete temperature were to increase from 55 to 60°F (13 to 16°C).

Regardless of the different cold weather provisions contained in current ACI committee documents, it's important to determine what surface and embedment temperatures may be detrimental to the concrete. This information can then be used to develop concreting strategies that provide effective, cost-efficient, and environmentally responsible protection of fresh concrete.

Cold Weather Concreting Strategies

Based on requirements and/or recommendations in the discussed ACI committee documents, cold weather concreting strategies for preventing early freezing and promoting strength development fall within two categories: placing concrete against cold formwork and reinforcing steel, and placing concrete against cold massive embedments.

When placing concrete against cold formwork and reinforcing steel surfaces, three strategies are provided (Fig. 1):

1. Use the warm concrete to heat the forms and reinforcing steel and then maintain the required concrete temperature by protection methods through the prescribed protection period (allowed by ACI 306.1-90[3]);
2. Heat the formwork and reinforcing steel to a minimum of 32°F (0°C), place the concrete, and then maintain the required concrete temperature by protection methods through the prescribed protection period (required by ACI 301-10[2] and recommended in ACI 306R-10[4]); or
3. Heat the forms and reinforcing steel to within 15°F (8°C) less than and 10°F (5°C) more than the as-placed concrete temperature, place the concrete, and then maintain the required concrete temperature by protection methods through the prescribed protection period (secondary recommendation in ACI 306R-10[4]).

When placing concrete against cold massive embedments, two strategies are provided (Fig. 2):

A. Heat cold massive metallic embedments (as designated by the specifier) to a minimum of 32°F (0°C), place the concrete, and then maintain the required concrete temperature by protection methods through the prescribed protection period (required by ACI 306.1-90[3] and ACI 301-10[2]; recommended by ACI 306R-10[4]); or
B. Heat cold massive metallic embedments (as designated by the specifier) to the temperature of the concrete, place the concrete, and then maintain the required concrete temperature by protection methods through the prescribed protection period (secondary recommendation in ACI 306R-10[4]).

The five strategies for both categories can be satisfied using one of the following options:

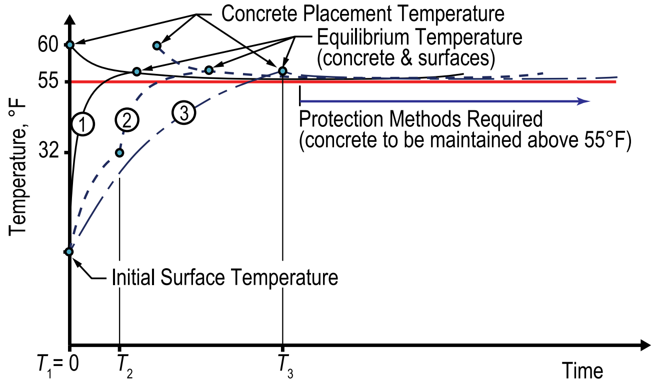

Fig. 1: Documents produced by ACI Committee 306 provide three options when placing concrete on cold forms and reinforcing steel: Option 1 is to allow heat from the fresh concrete to warm the cold surfaces, Option 2 is to warm the surfaces to 32°F (0°C) prior to placement by applying heat over time T_1 to T_2, and Option 3 is to warm the surfaces to a temperature ranging from 15°F (8°C) less than to 10°F (5°C) more than the concrete temperature by applying heat over time T_1 to T_3. The structure's embodied energy will increase accordingly (Note: °F = 1.8°C + 32)

- Require heating of cold surfaces and embedments to a minimum of 32°F (0°C);
- Require heating of cold surfaces and embedments to a temperature that is nearly the same as the as-placed concrete temperature; or
- Allow the as-placed concrete to warm the cold surfaces and embedments.

There are considerable differences in the amount of energy needed for each and thus the intrinsic energy associated with a project. While selection must be based on meeting the twin objectives of preventing concrete from early freezing and promoting concrete strength gain through the protection period, it must also be based on environmental impact and economic costs.

ACI 306R Objectives

Prevention of freezing

ACI 306R-10[4] lists the objectives of cold weather concreting practices. The main goal is to prevent damage to concrete due to early-age freezing. At about the time that concrete reaches a compressive strength of 500 psi (3.5 MPa), sufficient mixing water is expected to have combined with cement during hydration, thereby decreasing the degree of saturation of the concrete to below the critical level (level at which a single cycle of freezing causes damage). Most well-proportioned concrete mixtures reach this strength at 50°F (10°C) within 48 hours. If the concrete freezes before it reaches 500 psi (3.5 MPa), other ACI 306 objectives, such as strength gain and long-term durability, can't be accomplished.

When it comes to freshly placed concrete, only two possible mechanisms exist for early-age freezing: contact freezing or immersion freezing. For water to freeze on contact with a surface, it must be supercooled (cooled to

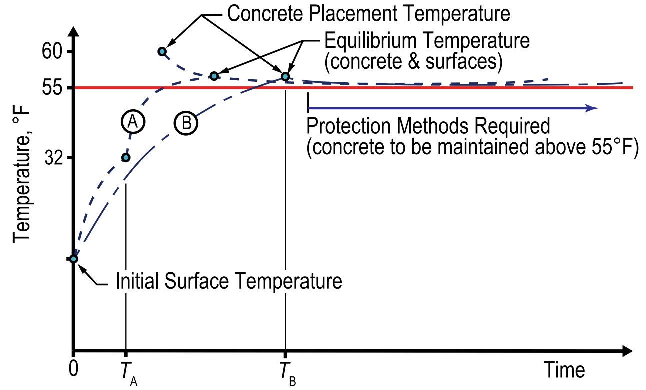

Fig. 2: Documents produced by ACI Committee 306 provide two options when placing concrete on cold massive embedments: Option A is to warm the surfaces to 32°F (0°C) prior to placement by applying heat over time 0 to T_A, and Option B is to warm the surfaces to the concrete temperature by applying heat over time 0 to T_B. The structure's embodied energy will increase accordingly

below 32°F [0°C]).[5] However, given the recommendations in ACI 306R-10,[4] ACI 306.1-90,[3] and ACI 301-10,[2] the minimum concrete temperature as placed must be at least 40°F (5°C). The mixing water will therefore be well above the freezing point, and contact freezing will not be possible, regardless of the temperature of the surface in contacts.

This can be demonstrated by pouring 50°F (10°C) water over any cold (below 32°F [0°C]) surface—the water won't freeze upon contact. However, it may still cool below 32°F (0°C) and freeze over time. This mechanism, immersion freezing, is what can occur in concrete.

When warm concrete is placed against cold surfaces, heat will transfer from the concrete to the cold materials and surrounding cold air. As a result, the concrete mixing water can cool sufficiently to reach the freezing point. Without supplemental heat, the concrete hydration can slow and extend the time needed to reach a strength of 500 psi (3.5 MPa). At the same time, this reduces the amount of heat the concrete generates internally and reduces the time needed for the cold surfaces and surrounding cold air to draw sufficient heat from the mixing water to cause freezing. Accelerators are often used in the concrete mixture to decrease the time it takes the concrete to reach 500 psi (3.5 MPa) and thus improve the odds that the concrete gains the necessary strength before mixing water freezes.

We recently demonstrated[6] that the mixing water in concrete placed at about 58°F (14°C) did not freeze when it came into contact with a No. 18 bar at –5°F (–21°C) (Fig. 3). Previous analytical work by Suprenant and Basham,[7] cited in ACI 306R-88,[8] included the assumption that concrete mixing water froze at 22°F (–6°C), while work by Swift et al.[9] assumed that the concrete mixing water froze when the concrete-reinforcing steel interface was below 32°F (0°C).

Our experimental results showed no freezing point plateaus for any of the concrete samples placed against cold steel. Based on this work, we can conclude that freezing of the concrete mixing water is not possible under the temperature conditions used in the study (concrete at about 60°F [16°C] and reinforcing steel at about –5°F [–21°C]).

It should be also noted that even a No. 18 bar comprising 5% of the gross volume of the specimen caused temperature drop in the concrete of only about 2°F (1.1°C) before it reached equilibrium with the steel. The recent experimental work also showed that the concrete heated up the reinforcing steel to 32°F (0°C) rather quickly. For reinforcing bars that are not considered massive embedments by ACI 306 (No. 9 bar or smaller), the test bars heated to 32°F (0°C) within 1 minute after concrete was placed. For the bars that are considered massive (No. 11, 14, and 18 bars), the concrete heated the bars to 32°F (0°C) within 5 minutes after concrete placement.

The Zero Law of Thermodynamics can be extended to predict the temperature of concrete cast against cold formwork surfaces and reinforcing steel. For example, if 58°F (15°C) concrete is cast against surfaces at –5°F (–21°C) (¾ in. [19 mm] plywood formwork and a No. 18 bar at a 5% concentration ratio), the equilibrium temperature will be about 53°F (12°C). However, immersion freezing is clearly not possible.

Strength gain

ACI documents recommend or require that the concrete be protected at minimum temperatures that range from 40 to 55°F (5 to 13°C). While concrete cannot freeze by contact and would be very difficult to freeze by immersion (may only be possible with massive embedments), this requirement keeps the concrete above freezing to promote strength gain. If the concrete is used to heat cold surfaces, it's likely to lose only about 5°F (3°C). Thus, the timing on when to use protection methods will be about the same as it would be if the surfaces were preheated before concrete placement.

There is also an interesting twist with respect to ACI 306R-10[4] recommended *minimum* concrete temperatures and ACI 301-10[2] and ACI 306.1-90[3] required *minimum* concrete temperatures. While all three documents use the same *minimum* concrete temperature as placed and maintained, ACI 306.1-90 provides contingency instructions:

"*Protection deficiency*—If the temperature requirements during the specified protection period are not met but the concrete was prevented from freezing, continue protection until twice the deficiency of protection in degree-hours is made up."

Thus, the "minimum" temperatures in ACI 306.1 can be violated with a protection deficiency plan in place. We are aware of cases in which the protection deficiency plan has been used. Typically, leaving insulating blankets in place for an extra day or two has been sufficient to make up the deficiency of protection in degree-hours.

Minimizing Concreting Issues

ACI 306R-10[4] recommends heating cold surfaces to avoid inconsistent setting, rapid moisture loss, and plastic shrinkage cracking. The recommendations are that cold surfaces should be heated to no more than 10°F (5°C) greater or 15°F (8°C) less than that of the concrete. These temperature limits are similar to what contractors anticipate when they place concrete in an enclosed building. But concrete is rarely placed in an enclosed building, and contractors are well aware of how cold temperatures can affect fresh concrete properties and finishing.

Further, because wall and column formwork will protect concrete from rapid moisture loss and plastic shrinkage cracking, it would appear that the temperature recommendation applies to exposed concrete flatwork.

Our tests showed that a cold bar surface had little effect on fresh concrete farther than 1 bar diameter away (Fig. 3). Also, numerical analyses conducted by Swift et al.[9] showed that variations in ambient air temperatures and formwork temperatures had negligible effects on the temperature at the concrete-steel interface. Taken together, it's apparent that cold surfaces located away from the exposed surface of

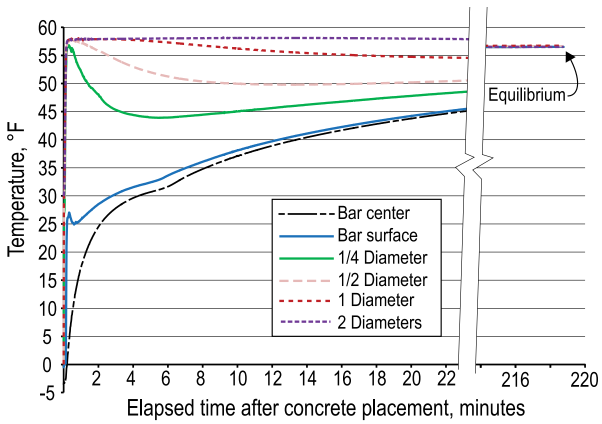

Fig. 3: Temperature readings for a No. 18 bar with a steel concentration ratio of 1%. The readings at the bar surface exhibit a slight temperature drop from 26 to 25°F (–3.3 to –3.9°C) at about 30 seconds. While a very small plateau is evident and could indicate the initial formation of ice, the plateau persists for only about 20 seconds. The amount of ice would be very small and would be melted as the concrete warmed the bar surface above 32°F (0°C). The temperature curves converge at about 220 minutes at an equilibrium temperature of 56.6°F (13.7°C). Based on the initial bar temperature of –4.1°F (–20°C) and the initial concrete temperature of 58.1°F (14.5°C), the calculated equilibrium temperature was 57.0°F (13.9°C)[6]

Fig. 4: Massive embedments are currently classified as steel sections larger than a No. 9 bar. Based on recent findings,[6] it is recommended that the massive embedment classification be increased to steel sections larger than a No. 18 bar (4 in.^{2} (2500 mm^2) cross-sectional area)

the concrete will not have significant effects on the concrete surface temperature. Therefore, it's not clear why the heating recommendations to minimize concreting issues are included in ACI 306R-10.

Recommendations for Cold Weather Strategies

Cold weather concreting strategies must protect the concrete from freezing and promote strength gain. Yet, the selected cold weather concreting strategy should also minimize the construction project's embodied energy.

Our previously published tests and discussions in this article can serve as the bases for three basic principles for developing cold weather concreting strategies:

- Neither contact nor immersion freezing of concrete mixing water is possible;
- Cold formwork and steel surfaces cause negligible decreases in the as-placed temperature of concrete; and
- Massive steel sections—those with cross-sectional areas larger than a No. 18 bar (4 in.^{2} [2500 mm^2]) (Fig. 4)—at temperatures of at least 10°F (–12°C)—will not freeze mixing water in concrete placed at a temperature of 55°F (13°C) or higher.

We further note that contractors' experiences with cold weather concreting confirm that:

- Heating of cold surfaces is a time-consuming and costly process. Depending on ambient conditions and project size, it can take 24 to 72 hours to heat formwork and reinforcing steel to above 32°F (0°C);
- Although a contractor will anticipate when concrete is to be placed and thus start heating cold surfaces accordingly, it's common to continue heating the surfaces even if the placement has to be delayed. This increases the cost of cold weather concreting yet provides no benefit to the concrete; and
- Because cold temperatures can affect the productivity of labor and equipment as well as the behavior of fresh concrete, there are practical limits for concreting operations. These can vary by location, but a practical temperature limit of –4°F (–20°C) has been reported in the literature.[10]

Based on the basic principles and contractor experiences, we propose the following cold weather concreting strategies for cold surfaces, massive embedments, and strength gain:

- **Cold Surfaces**—Recent research verifies that fresh concrete can be placed in contact with bars as cold as –5°F (–21°C) without detrimental effects. A conservative standard of practice would be to avoid placing fresh concrete on surfaces colder than 10°F (–12°C). This would generally eliminate the need to heat reinforcing steel and formwork prior to placement, resulting in a more sustainable solution to cold weather concreting;
- **Cold Massive Embedments**—The architect/engineer should identify on the contract documents those embedments that are considered massive and therefore will require heating. Based on the work by Kozikowski et al.[6] a steel member with a cross-sectional area larger than 4 in.^{2} (2500 mm^2) may be considered a massive embedment. Where the contract documents have identified massive embedments, these must be heated to 32°F (0°C) prior to concrete placement; and
- **Protection and Strength Gain**—Efficient strength gain is promoted in cold weather when freshly placed concrete meets the minimum ACI placement and maintenance requirements (Table 5.1 of ACI 306R-10[4]) during the specified protection period. However, if the temperature recommendations during the protection period are not met but the concrete was prevented from freezing, the protection period must be extended to obtain a strength equivalent to that which would have been reached during a shorter duration of warmer protection.

Note that these recommendations do not apply to placing concrete on ground. Other work is currently under way by ACI 306 members to measure the effect of cold subgrades on freshly placed concrete.

References

1. Korhonen, C.J., "Off-the-Shelf Antifreeze Admixtures," U.S. Army Corps of Engineers, Cold Regions Research and Engineering Laboratory, ERDC/CRREL TR-02-7, Apr. 2002.

2. ACI Committee 301, "Specifications for Structural Concrete (ACI 301-10)," American Concrete Institute, Farmington Hills, MI, 2010, 77 pp.

3. ACI Committee 306, "Standard Specification for Cold Weather Concreting (306.1-90) (Reapproved 2002)," American Concrete Institute, Farmington Hills, MI, 5 pp.

4. ACI Committee 306, "Guide to Cold Weather Concreting (ACI 306R-10)," American Concrete Institute, Farmington Hills, MI, 2010, 26 pp.

5. Ladino Moreno, L.A.; Stetzer, O.; and Lohmann, U., "Contact Freezing: A Review of Experimental Studies," *Atmospheric Chemistry and Physics*, V. 13, No. 19, 2013, pp. 9745-9769.

6. Kozikowski, R.; McCall, W.C.; and Suprenant, B.A., "How Does Cold Reinforcing Steel Affect Fresh Concrete?" *Concrete International*, V. 36, No. 4, Apr. 2014, pp. 49-56.

7. Suprenant, B.A., and Basham, K.D., "Effects of Cold Embedments on the Temperature of Fresh Concrete," *Proceedings*, Third RILEM International Symposium on Winter Concreting, Technical Research Center of Finland, (VTT), Espoo, Finland, 1985.

8. ACI Committee 306, "Cold Weather Concreting (ACI 306R-88)," American Concrete Institute, Farmington Hills, MI, 1988, 23 pp.

9. Swift, D.P.; Puckett, J.A.; and Edgar, T.V., "Finite Element Analysis of Cold Embedments in Fresh Concrete," *Journal of Cold Regions Engineering*, ASCE, V. 6, No. 2, June 1992, pp. 41-57.

10. Havers, J.A., and Morgan, R.M., "Literature Survey of Cold Weather Construction Practices," *SR 172*, U.S. Army Corps of Engineers, Cold Regions Research and Engineering Laboratory, Hanover, NH, 1972, 181 pp.

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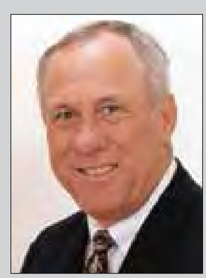

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