Concrete can be placed safely without damage from freezing throughout the winter months in cold climates if certain precautions are taken. Cold weather is defined by ACI Committee 306 as a period when for more than 3 successive days the average daily air temperature drops below 5°C (40°F) and stays below 10°C (50°F) for more than one-half of any 24 hour period. Under these circumstances, all materials and equipment needed for adequate protection and curing must be on hand and ready for use before concrete placement is started. Normal concreting practices can be resumed once the ambient temperature is above 10°C (50°F) for more than half a day.

During cold weather, the concrete mixture and its temperature should be adapted to the construction procedure and ambient weather conditions. Preparations should be made to protect the concrete; enclosures, windbreaks, portable heaters, insulated forms, and blankets should be ready to maintain the concrete temperature (Fig. 14-1). Forms, reinforcing steel, and embedded fixtures must be clear of snow and ice at the time concrete is placed. Thermometers and proper storage facilities for test cylinders should be available to verify that precautions are adequate.

**EFFECT OF FREEZING FRESH CONCRETE**

Concrete gains very little strength at low temperatures. Freshly mixed concrete must be protected against the disruptive effects of freezing (Fig.14-2) until the degree of saturation of the concrete has been sufficiently reduced by the process of hydration. The time at which this reduction is accomplished corresponds roughly to the time required for the concrete to attain a compressive strength of 3.5 MPa (500 psi) (Powers 1962). At normal temperatures and water-cement ratios less than 0.60, this occurs within the first 24 hours after placement. Significant ultimate strength reductions, up to about 50%, can occur if concrete is frozen within a few hours after placement or before it attains a compressive strength of 3.5 MPa (500 psi) (McNeese 1952). Concrete to be exposed to deicers should attain a strength of 28 MPa (4,000 psi) prior to repeated cycles of freezing and thawing (Klieger 1957).

Concrete that has been frozen just once at an early age can be restored to nearly normal strength by providing favorable subsequent curing conditions. Such concrete, however, will not be as resistant to weathering nor as watertight as concrete that had not been frozen. The critical period after which concrete is not seriously damaged by one or two freezing cycles...
is dependent upon the concrete ingredients and conditions of mixing, placing, curing, and subsequent drying. For example, air-entrained concrete is less susceptible to damage by early freezing than non-air-entrained concrete. See Chapter 8, “Air-Entrained Concrete,” for more information.

**STRENGTH GAIN OF CONCRETE AT LOW TEMPERATURES**

Temperature affects the rate at which hydration of cement occurs—low temperatures retard hydration and consequently retard the hardening and strength gain of concrete.

If concrete is frozen and kept frozen above about minus 10°C (14°F), it will gain strength slowly. Below that temperature, cement hydration and concrete strength gain cease. Fig. 14-3 illustrates the effect of cool temperatures on setting time. Fig. 14-4 illustrates the effects of casting temperature on slump. Figs. 14-5 and 14-6 show the age-compressive strength relationship for concrete that has been cast and cured at various temperatures. Note in Fig. 14-6 that concrete cast and cured at 4°C (40°F) and 13°C (55°F) had relatively low strengths for the first week; but after 28 days—when all specimens were moist-cured at 23°C (73°F)—strengths for the 4°C (40°F) and 13°C (55°F) concretes grew faster than the 23°C (73°F) concrete and at one year they were slightly higher.
Higher-early strengths can be achieved through use of Type III high-early-strength cement as illustrated in Fig. 14-7. Principal advantages occur during the first 7 days. At a 4°C (40°F) curing temperature, the advantages of Type III cement are more pronounced and persist longer than at the higher temperature.

HEAT OF HYDRATION

Concrete generates heat during hardening as a result of the chemical process by which cement reacts with water to form a hard, stable paste. The heat generated is called heat of hydration; it varies in amount and rate for different cements. Dimensions of the concrete placement, ambient air temperature, initial concrete temperature, water-cement ratio, admixtures, and the composition, fineness, and amount of cementitious material all affect heat generation and buildup.

Heat of hydration is useful in winter concreting as it contributes to the heat needed to provide a satisfactory curing temperature; often without other temporary heat sources, particularly in more massive elements.

Concrete must be delivered at the proper temperature and account must be taken of the temperature of forms, reinforcing steel, the ground, or other concrete on which the fresh concrete is cast. Concrete should not be cast on frozen concrete or on frozen ground.

Fig. 14-8 shows a concrete pedestal being covered with a tarpaulin just after the concrete was placed. Tarpaulins and insulated blankets are often necessary to retain the heat of hydration more efficiently and keep the concrete as warm as possible. Thermometer readings of
Chlorides are not recommended for concretes exposed to soil or water containing sulfates or for concretes susceptible to alkali-aggregate reaction.

Accelerators must not be used as a substitute for proper curing and frost protection. Specially designed accelerating admixtures allow concrete to be placed at temperatures down to -7°C (20°F). The purpose of these admixtures is to reduce the time of initial setting, but not necessarily to speed up strength gain. Covering concrete to keep out moisture and to retain heat of hydration is still necessary. Furthermore, traditional antifreeze solutions, as used in automobiles, should never be used; the quantity of these materials needed to appreciably lower the freezing point of concrete is so great that strength and other properties can be seriously affected.

Since the goal of using special mixtures during cold weather concreting is to reduce the time of setting, a low water-cement ratio, low-slump concrete is particularly desirable, especially for cold-weather flatwork; concrete mixtures with higher slumps usually take longer to set. In addition, evaporation is minimized so that finishing can be accomplished quicker (Fig. 14-9).

**AIR-ENTRAINED CONCRETE**

Entrained air is particularly desirable in any concrete placed during freezing weather. Concrete that is not air entrained can suffer strength loss and internal as well as surface damage as a result of freezing and thawing (Fig. 14-10). Air entrainment provides the capacity to absorb stresses due to ice formation within the concrete. See Chapter 8, “Air-Entrained Concrete.”

The concrete’s temperature will tell whether the covering is adequate. The heat liberated during hydration will offset to a considerable degree the loss of heat during placing, finishing, and early curing operations. As the heat of hydration slows down, the need to cover the concrete becomes more important.

**SPECIAL CONCRETE MIXTURES**

High strength at an early age is desirable in winter construction to reduce the length of time temporary protection is required. The additional cost of high-early-strength concrete is often offset by earlier reuse of forms and shores, savings in the shorter duration of temporary heating, earlier setting times that allows the finishing of flatwork to begin sooner, and earlier use of the structure. High-early-strength concrete can be obtained by using one or a combination of the following:

1. Type III or HE high-early-strength cement
2. Additional portland cement (60 to 120 kg/m³ or 100 to 200 lb/yd³)
3. Chemical accelerators

Small amounts of an accelerator such as calcium chloride (at a maximum dosage of 2% by weight of portland cement) can be used to accelerate the setting and early-age strength development of concrete in cold weather. Accelerators containing chlorides should not be used where there is an in-service potential for corrosion, such as in concrete members containing steel reinforcement or where aluminum or galvanized inserts will be used.
Air entrainment should always be used for construction during the freezing months. The exception is concrete work done under roof where there is no chance that rain, snow, or water from other sources can saturate the concrete and where there is no chance of freezing.

The likelihood of water saturating a concrete floor during construction is very real. Fig. 14-11 shows conditions in the upper story of an apartment building during winter construction. Snow fell on the top deck. When heaters were used below to warm the deck, the snow melted. Water ran through floor openings down to a level that was not being heated. The water-saturated concrete froze, which caused a strength loss, particularly at the floor surface. This could also result in greater deflection of the floor and a surface that is less wear-resistant than it might have been.

**TEMPERATURE OF CONCRETE**

**Temperature of Concrete as Mixed**

The temperature of fresh concrete as mixed should not be less than shown in Lines 1, 2, or 3 of Table 14-1 for the respective thickness of section. Note that lower concrete temperatures are recommended for more massive concrete sections because heat generated during hydration is dissipated less rapidly in heavier sections. Also note that at lower ambient air temperatures more heat is lost from concrete during transporting and placing; hence, the recommended concrete temperatures as mixed are higher for colder weather.

### Table 14-1. Recommended Concrete Temperature for Cold-Weather Construction—Air-Entrained Concrete*

<table>
<thead>
<tr>
<th>Line</th>
<th>Condition</th>
<th>Thickness of sections, mm (in.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Less than 300 (12)</td>
</tr>
<tr>
<td>1</td>
<td>Minimum temperature of fresh concrete as mixed for weather indicated.</td>
<td>Above -1°C (30°F)</td>
</tr>
<tr>
<td>2</td>
<td>-18°C to -1°C (0°F to 30°F)</td>
<td>18°C (65°F)</td>
</tr>
<tr>
<td>3</td>
<td>Below -18°C (0°F)</td>
<td>21°C (70°F)</td>
</tr>
<tr>
<td>4</td>
<td>Minimum temperature of fresh concrete as placed and maintained.**</td>
<td>13°C (55°F)</td>
</tr>
</tbody>
</table>

* Adapted from Table 3.1 of ACI 306R-88.

** Placement temperatures listed are for normal-weight concrete. Lower temperatures can be used for lightweight concrete if justified by tests.

For recommended duration of temperatures in Line 4, see Table 14-3.
There is little advantage in using fresh concrete at a temperature much above 21°C (70°F). Higher concrete temperatures do not afford proportionately longer protection from freezing because the rate of heat loss is greater. Also, high concrete temperatures are undesirable since they increase thermal shrinkage after hardening, require more mixing water for the same slump, and contribute to the possibility of plastic-shrinkage cracking (caused by rapid moisture loss through evaporation). Therefore, the temperature of the concrete as mixed should not be more than 5°C (10°F) above the minimums recommended in Table 14-1.

**Aggregate Temperature.** The temperature of aggregates varies with weather and type of storage. Aggregates usually contain frozen lumps and ice when the temperature is below freezing. Frozen aggregates must be thawed to avoid pockets of aggregate in the concrete after batching, mixing, and placing. If thawing takes place in the mixer, excessively high water contents in conjunction with the cooling effect due to the ice melting must be avoided.

At temperatures above freezing it is seldom necessary to heat aggregates, the desired concrete temperature can usually be obtained by heating only the mixing water. At temperatures below freezing, in addition to heating the mixing water, often only the fine aggregate needs to be heated to produce concrete of the required temperature, provided the coarse aggregate is free of frozen lumps.

Three of the most common methods for heating aggregates are: (1) storing in bins or weigh hoppers heated by steam coils or live steam; (2) storing in silos heated by hot air or steam coils; and (3) stockpiling over heated slabs, stem vents or pipes. Although heating aggregates stored in bins or weigh hoppers is most commonly used, the volume of aggregate that can be heated is often limited and quickly consumed during production. Circulating steam through pipes over which aggregates are stockpiled is a recommended method for heating aggregates. Stockpiles can be covered with tarpaulins to retain and distribute heat and to prevent formation of ice. Live steam, preferably at pressures of 500 to 900 kPa (75 to 125 psi), can be injected directly into the aggregate pile to heat it, but the resultant variable moisture content in aggregates might result in erratic mixing-water control.

On small jobs aggregates can be heated by stockpiling over metal culvert pipes in which fires are maintained. Care should be taken to prevent scorching the aggregates.

**Mixing-Water Temperature.** Of the ingredients used to make concrete, mixing water is the easiest and most practical to heat. The mass of aggregates and cement in concrete is much greater than the mass of water; however, water can store about five times as much heat as can cement and aggregate of the same weight. For cement and aggregates, the average specific heat (that is, heat units required to raise the temperature 1°C (1°F) per kg (lb) of material) can be assumed as 0.925 kJ (0.22 Btu) compared to 4.187 kJ (1.0 Btu) for water.

Fig. 14-12 shows the effect of temperature of materials on temperature of fresh concrete. The chart is based on the equation

\[
T = \frac{0.22(T_a M_a + T_c M_c) + T_w M_w + T_{wa} M_{wa}}{0.22(M_a + M_c + M_w + M_{wa})}
\]

where

- \(T\) = temperature in degrees Celsius (Fahrenheit) of the fresh concrete
- \(T_a, T_c, T_w,\) and \(T_{wa}\) = temperature in degrees Celsius (Fahrenheit) of the aggregates, cement, added mixing water, and free moisture on aggregates, respectively; generally \(T_a = T_{wa}\)
- \(M_a, M_c, M_w,\) and \(M_{wa}\) = mass in kilograms (pounds) of the aggregates, cement, free moisture on aggregates, and mixing water, respectively

If the weighted average temperature of aggregates and cement is above 0°C (32°F), the proper mixing-water temperature for the required concrete temperature can be selected from Fig. 14-12. The range of concrete temperatures in the chart corresponds with the recommended values given in Lines 1, 2, and 3 of Table 14-1.

**Fig. 14-12.** Temperature of mixing water needed to produce heated concrete of required temperature. Temperatures are based on the mixture shown but are reasonably accurate for other typical mixtures.
To avoid the possibility of a quick or flash set of the concrete when either water or aggregates are heated to above 38°C (100°F), they should be combined in the mixer first before the cement is added. If this mixer-loading sequence is followed, water temperatures up to the boiling point can be used, provided the aggregates are cold enough to reduce the final temperature of the aggregates and water mixture to appreciably less than 38°C (100°F).

Fluctuations in mixing-water temperature from batch to batch should be avoided. The temperature of the mixing water can be adjusted by blending hot and cold water.

Temperature of Concrete as Placed and Maintained

There will be some temperature loss after mixing while the truck mixer is traveling to the construction site and waiting to discharge its load. The concrete should be placed in the forms before its temperature drops below that given on Line 4 of Table 14-1; that concrete temperature should be maintained for the duration of the protection period given in Chapter 12 under “Curing Period and Temperature.”

Cooling After Protection

To avoid cracking of the concrete due to sudden temperature change near the end of the curing period, ACI Committee 306 requires that the source of heat and cover protection be slowly removed. The maximum allowable temperature drop during the first 24 hours after the end of the protection is given in Table 14-2. The temperature drops apply to surface temperatures. Notice that the cooling rates for surfaces of mass concrete (thick sections) are lower than for thinner members.

CONTROL TESTS

Thermometers are needed to check the concrete temperatures as delivered, as placed, and as maintained. An inexpensive pocket thermometer is shown in Fig. 14-13.

After the concrete has hardened, temperatures can be checked with special surface thermometers or with an ordinary thermometer that is kept covered with insulating blankets. A simple way to check temperature below the concrete surface is shown in Fig. 14-14. Instead of filling the hole shown in Fig. 14-14 with a fluid, it can be fitted with insulation except at the bulb.

Concrete test cylinders must be maintained at a temperature between 16°C (60°F) and 27°C (80°F) at the jobsite for up to 48 hours until they are taken to a laboratory for curing (ASTM C 31 or AASHTO T 23). For concrete mixtures with a specified strength of 40 MPa (6,000 psi) or greater, the initial curing temperature shall be between 20°C and 26°C (68°F and 78°F). During this period, cylinders should be kept in a curing box and covered with a nonabsorptive, nonreactive plate or impervious plastic bag; the temperature in the box should be accurately con-

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**Table 14-2. Maximum Allowable Temperature Drop During First 24 Hours After End of Protection Period**

<table>
<thead>
<tr>
<th>Section size, minimum dimensions, mm (in.)</th>
<th>Less than 300 (12)</th>
<th>300 to 900 (12 to 36)</th>
<th>900 to 1800 (36 to 72)</th>
<th>Over 1800 (72)</th>
</tr>
</thead>
<tbody>
<tr>
<td>28°C (50°F)</td>
<td>22°C (40°F)</td>
<td>17°C (30°F)</td>
<td>11°C (20°F)</td>
<td></td>
</tr>
</tbody>
</table>

* Adapted from Table 5.5 of ACI 306R-88.
trolled by a thermostat (Fig. 14-15). When stored in an insulated curing box outdoors, cylinders are less likely to be jostled by vibrations than if left on the floor of a trailer. If kept in a trailer where the heat may be turned off at night or over a weekend or holiday, the cylinders would not be at the prescribed curing temperatures during this critical period.

In addition to laboratory-cured cylinders, it is useful to field-cure some test cylinders in order to monitor actual curing conditions on the job in cold weather. It is sometimes difficult to find the right locations for field curing. Differences in the surface to volume ratios between cylinders and the structure, in conjunction with differences in mass, make correlating field-cured cylinder strengths to in-place strengths difficult. A preferred location is in a boxout in a floor slab or wall with thermal insulation for cover. When placed on a formwork ledge just below a heated, suspended floor, possible high temperatures there will not duplicate the average temperature in the slab, nor the lowest temperature on top of the slab. Still, field-cured cylinders are more indicative of actual concrete strength than laboratory-cured cylinders. Particular care should be taken to protect compressive strength test cylinders from freezing; their small mass may not generate enough heat of hydration to protect them.

Molds stripped from cylinders after the first 24 ± 8 hours must be wrapped tightly in plastic bags or laboratory curing started immediately. When cylinders are picked up for delivery to the laboratory, they must be maintained at a temperature of 16°C (60°F) to 27°C (80°F) until they are placed in the laboratory curing room.

Cast-in-place cylinders (ASTM C 873) and non-destructive testing methods discussed in Chapter 16, as well as maturity techniques discussed later in this chapter, are helpful in monitoring in-place concrete strength.

**CONCRETING ON GROUND**

Concreting on ground during cold weather involves some extra effort and expense, but many contractors find that it more than pays for itself. In winter, the site around the structure may be frozen rather than a morass of mud. The concrete will furnish some if not all of the heat needed for proper curing. Internal concrete temperatures should be monitored. Insulated blankets or simple enclosures are easily provided. Embankments are frozen and require less bracing. With a good start during the winter months, construction gets above the ground before warmer weather arrives.

Placing concrete on the ground involves different procedures from those used at an upper level: (1) the ground must be thawed before placing concrete; (2) cement hydration will furnish some of the curing heat; (3) construction of enclosures is much simpler and use of insulating blankets may be sufficient; (4) in the case of a floor slab, a vented heater is required if the area is enclosed; and (5) hydronic heaters can be used to thaw subgrades using insulated blankets or to heat enclosures without concern for carbonation. For more on hydronic heaters, see “Heaters” later in this chapter.

Once cast, footings should be backfilled as soon as possible with unfrozen fill. Concrete should never be placed on a frozen subgrade or backfilled with frozen fill; otherwise once they thaw, uneven settlements may occur causing cracking.

ACI Committee 306 requires that concrete not be placed on any surface that would lower the temperature of the concrete in place below the minimum values shown on Line 4 in Table 14-1. In addition, concrete placement temperatures should not be higher than these minimum values by more than 11°C (20°F) to reduce rapid moisture loss and the potential development of plastic shrinkage cracks.

When the subgrade is frozen to a depth of approximately 80 mm (3 inches), the surface region can be thawed by (1) steaming; (2) spreading a layer of hot sand, gravel, or other granular material where the grade elevations allow it; (3) removing and replacing with unfrozen fill; (4) covering the subgrade with insulation for a few days; or (5) using hydronic heaters under insulated blankets which can thaw frozen ground at a rate of 0.3 m (1 ft) per 24 hours to a depth up to 3 m (10 ft) (Grochoski 2000). Placing concrete for floor slabs and exposed footings should be delayed until the ground thaws and warms sufficiently to ensure that it will not freeze again during the protection and curing period.

Slabs can be cast on ground at ambient temperatures as low as 2°C (35°F) as long as the minimum concrete temperature as placed is not less than shown on Line 4 of Table 14-1. Although surface temperatures need not be higher than a few degrees above freezing, they also should preferably not be more than 5°C (10°F) higher than the minimum placement temperature either. The duration of curing should not be less than that described in Chapter 12 for the
appropriate exposure classification. Because of the risk of surface imperfections that might occur on exterior concrete placed in late fall and winter, many concrete contractors choose to delay concrete placement until spring. By waiting until spring, temperatures will be more favorable for cement hydration; this will help generate adequate strengths along with sufficient drying so the concrete can resist freeze-thaw damage.

CONCRETING ABOVEGROUND

Working aboveground in cold weather usually involves several different approaches compared to working at ground level:

1. The concrete mixture need not be changed to generate more heat because portable heaters can be used to heat the undersides of floor and roof slabs. Nevertheless, there are advantages to having a mix that will produce a high strength at an early age; for example, artificial heat can be cut off sooner (see Table 14-3), and forms can be recycled faster.
2. Enclosures must be constructed to retain the heat under floor and roof slabs.
3. Portable heaters used to warm the underside of formed concrete can be direct-fired heating units (without venting).

Before placing concrete, the heaters under a formed deck should be turned on to preheat the forms and melt any snow or ice remaining on top. Temperature requirements for surfaces in contact with fresh concrete are the same as those outlined in the previous section “Concreting on Ground.” Metallic embedments at temperatures below the freezing point may result in local freezing that decreases the bond between concrete and steel reinforcement. ACI Committee 306 suggests that a reinforcing bar having a cross-sectional area of about 650 mm² (1 in.²) should have a temperature of at least -12°C (10°F) immediately before being surrounded by fresh concrete at a temperature of at least 13°C (55°F). Caution and additional study are required before definitive recommendations can be formulated. See ACI 306 for additional information.

When slab finishing is completed, insulating blankets or other insulation must be placed on top of the slab to ensure that proper curing temperatures are maintained. The insulation value (R) necessary to maintain the concrete surface temperature of walls and slabs above-ground at 10°C (50°F) or above for 7 days may be estimated from Fig. 14-16. To maintain a temperature for longer periods, more insulation is required. ACI 306 has additional graphs and tables for slabs placed on ground at

### Table 14-3.

**A. Recommended Duration of Concrete Temperature in Cold Weather–Air-Entrained Concrete**

<table>
<thead>
<tr>
<th>Service category</th>
<th>Protection from early-age freezing</th>
<th>For safe stripping strength</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Conventional concrete,** days</td>
<td>High-early strength concrete,† days</td>
</tr>
<tr>
<td></td>
<td>Conventional concrete,** days</td>
<td>High-early-strength concrete,† days</td>
</tr>
<tr>
<td>No load, not exposed; favorable moist-curing</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>No load, exposed, but later has favorable moist-curing</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Partial load, exposed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fully stressed, exposed</td>
<td>6</td>
<td>4</td>
</tr>
</tbody>
</table>

* Adapted from Tables 5.1 and 5.3 of ACI 306. Cold weather is defined as that in which average daily temperature is less than 4°C (40°F) for 3 successive days except that if temperatures above 10°C (50°F) occur during at least 12 hours in any day, the concrete should no longer be regarded as winter concrete and normal curing practice should apply. For recommended concrete temperatures, see Table 14-1. For concrete that is not air entrained, ACI Committee 306 states that protection for durability should be at least twice the number of days listed in Table A. Part B was adapted from Table 6.8 of ACI 306R-88. The values shown are approximations and will vary according to the thickness of concrete, mix proportions, etc. They are intended to represent the ages at which supporting forms can be removed. For recommended concrete temperatures, see Table 14-1.

** Made with ASTM Type I, II, GU, or MS portland cement.
† Made with ASTM Type III or HE cement, or an accelerator, or an extra 60 kg/m³ (100 lb/yd³) of cement.
‡ “Exposed” means subject to freezing and thawing.
Corners and edges are particularly vulnerable during cold weather. As a result, the thickness of insulation for these areas, especially on columns, should be about three times the thickness that is required to maintain the same for walls or slabs. On the other hand, if the ambient temperature rises much above the temperature assumed in selecting insulation values, the temperature of the concrete may become excessive. This increases the probability of thermal shock and cracking when forms are removed. Temperature readings of insulated concrete should therefore be taken at regular intervals and should not vary from ambient air temperatures by more than the values given in ACI 306. In addition, insulated concrete temperatures should not be allowed to rise much above 27°C (80°F). In case of a sudden increase in concrete temperature, up to say 35°C (95°F), it may be necessary to remove some of the insulation or loosen the formwork. The maximum temperature differential between the concrete interior and the concrete surface should be about 20°C (35°F) to minimize cracking. The weather forecast

Fig. 14-16. Thermal resistance (R) of insulation required to maintain the concrete surface temperature of walls and slabs aboveground at 10°C (50°F) or above for 7 days. Concrete temperature as placed: 10°C (50°F). Maximum wind velocity: 24 km/h (15 mph). Note that in order to maintain a certain minimum temperature for a longer period of time, more insulation or a higher R value is required (adapted from ACI 306).
should be checked and appropriate action taken for expected temperature changes. Columns and walls should not be cast on foundations at temperatures below 0°C (32°F) because chilling of concrete in the bottom of the column or wall will retard strength development. Concrete should not be placed on any surface that would lower the temperature of the as-placed concrete below the minimum values shown on Line 4 in Table 14-1.

**ENCLOSURES**

Heated enclosures are very effective for protecting concrete in cold weather, but are probably the most expensive too (Fig. 14-17). Enclosures can be of wood, canvas tarpaulins, or polyethylene film (Fig. 14-18). Prefabricated, rigid-plastic enclosures are also available. Plastic enclo-

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**Table 14-4. Insulation Values of Various Materials**

<table>
<thead>
<tr>
<th>Material</th>
<th>Density kg/m³ (lb/ft³)</th>
<th>Thermal resistance, $R$, for 10-mm (1-in.) thickness of material,* ((\text{m}^2 \cdot \text{K})/\text{W}) ((\text{°F} \cdot \text{hr} \cdot \text{ft}^2)/\text{Btu})</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Board and Slabs</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Expanded polyurethane</td>
<td>24 (1.5)</td>
<td>0.438 (6.25)</td>
</tr>
<tr>
<td>Expanded polystyrene, extruded smooth-skin surface</td>
<td>29 to 56 (1.8 to 3.5)</td>
<td>0.347 (5.0)</td>
</tr>
<tr>
<td>Expanded polystyrene, extruded cut-cell surface</td>
<td>29 (1.8)</td>
<td>0.277 (4.0)</td>
</tr>
<tr>
<td>Glass fiber, organic bonded</td>
<td>64 to 144 (4 to 9)</td>
<td>0.277 (4.0)</td>
</tr>
<tr>
<td>Expanded polystyrene, molded beads</td>
<td>16 (1)</td>
<td>0.247 (3.85)</td>
</tr>
<tr>
<td>Mineral fiber with resin binder</td>
<td>240 (15)</td>
<td>0.239 (3.45)</td>
</tr>
<tr>
<td>Mineral fiberboard, wet felted</td>
<td>256 to 272 (16 to 17)</td>
<td>0.204 (2.94)</td>
</tr>
<tr>
<td>Vegetable fiberboard sheathing</td>
<td>288 (18)</td>
<td>0.182 (2.64)</td>
</tr>
<tr>
<td>Cellular glass</td>
<td>136 (8.5)</td>
<td>0.201 (2.86)</td>
</tr>
<tr>
<td>Laminated paperboard</td>
<td>480 (30)</td>
<td>0.139 (2.00)</td>
</tr>
<tr>
<td>Particle board (low density)</td>
<td>590 (37)</td>
<td>0.128 (1.85)</td>
</tr>
<tr>
<td>Plywood</td>
<td>545 (34)</td>
<td>0.087 (1.24)</td>
</tr>
<tr>
<td><strong>Loose fill</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wood fiber, soft woods</td>
<td>32 to 56 (2.0 to 3.5)</td>
<td>0.231 (3.33)</td>
</tr>
<tr>
<td>Perlite (expanded)</td>
<td>80 to 128 (5.0 to 8.0)</td>
<td>0.187 (2.70)</td>
</tr>
<tr>
<td>Vermiculite (exfoliated)</td>
<td>64 to 96 (4.0 to 6.0)</td>
<td>0.157 (2.27)</td>
</tr>
<tr>
<td>Vermiculite (exfoliated)</td>
<td>112 to 131 (7.0 to 8.2)</td>
<td>0.148 (2.13)</td>
</tr>
<tr>
<td>Sawdust or shavings</td>
<td>128 to 240 (8.0 to 15.0)</td>
<td>0.154 (2.22)</td>
</tr>
</tbody>
</table>

**Fig. 14-17.** Even in the winter, an outdoor swimming pool can be constructed if a heated enclosure is used. (43453)

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the minimum required on Line 4 in Table 14-1, additional insulating material, or material with a higher $R$ value, should be applied. Corners and edges of concrete are most vulnerable to freezing. In view of this, temperatures at these locations should be checked often.

The thermal resistance ($R$) values for common insulating materials are given in Table 14-4. For maximum efficiency, insulating materials should be kept dry and in close contact with concrete or formwork.

Concrete pavements can be protected from cold weather by spreading 300 mm (1 ft) or more of dry straw or hay on the surface for insulation. Tarpaulins, polyethylene film, or waterproof paper should be used as a protective cover over the straw or hay to make the insulation more effective and prevent it from blowing away. The straw or hay should be kept dry or its insulation value will drop considerably.

Stay-in-place insulating concrete forms became popular for cold-weather construction in the 1990s (Fig. 14-20). Insulating concrete forms (ICF) permit concreting in cold weather. (69699)

Fig. 14-18. (top) Tarpaulin heated enclosure maintains an adequate temperature for proper curing and protection during severe and prolonged winter weather. (bottom) Polyethylene plastic sheets admitting daylight are used to fully enclose a building frame. The temperature inside is maintained at 10°C (50°F) with space heaters. (69877, 69878)

Fig. 14-19. Stack of insulating blankets. These blankets trap heat and moisture in the concrete, providing beneficial curing. (43460)

INSULATING MATERIALS

Heat and moisture can be retained in the concrete by covering it with commercial insulating blankets or batt insulation (Fig. 14-19). The effectiveness of insulation can be determined by placing a thermometer under it and in contact with the concrete. If the temperature falls below

Fig. 14-20. Insulating concrete forms (ICF) permit concreting in cold weather. (69699)
14-20). Forms built for repeated use often can be economically insulated with commercial blanket or batt insulation. The insulation should have a tough moisture-proof covering to withstand handling abuse and exposure to the weather. Rigid insulation can also be used (Fig. 14-21).

Insulating blankets for construction are made of fiberglass, sponge rubber, open-cell polyurethane foam, vinyl foam, mineral wool, or cellulose fibers. The outer covers are made of canvas, woven polyethylene, or other tough fabrics that will withstand rough handling. The R value for a typical insulating blanket is about 1.2 m²·°C/W (5.6 [°F · hr · ft²] /Btu). (43461)

14-20). Forms built for repeated use often can be economically insulated with commercial blanket or batt insulation. The insulation should have a tough moisture-proof covering to withstand handling abuse and exposure to the weather. Rigid insulation can also be used (Fig. 14-21).

Insulating blankets for construction are made of fiberglass, sponge rubber, open-cell polyurethane foam, vinyl foam, mineral wool, or cellulose fibers. The outer covers are made of canvas, woven polyethylene, or other tough fabrics that will withstand rough handling. The R value for a typical insulating blanket is about 1.2 m²·°C/W for 50 to 70 mm thickness, 7(°F · hr · ft²)/Btu, but since R values are not marked on the blankets, their effectiveness should be checked with a thermometer. If necessary, they can be used in two or three layers to attain the desired insulation.

HEATERS

Three types of heaters are used in cold-weather concrete construction: direct fired, indirect fired, and hydronic systems (Figs. 14-22 to 14-25). Indirect-fired heaters are vented to remove the products of combustion. Where heat is to be supplied to the top of fresh concrete—for example, a floor slab—vented heaters are required. Carbon dioxide
(CO₂) in the exhaust must be vented to the outside and prevented from reacting with the fresh concrete (Fig. 14-23). Direct-fired units can be used to heat the enclosed space beneath concrete placed for a floor or a roof deck (Fig. 14-24).

Hydronic systems transfer heat by circulating a glycol/water solution in a closed system of pipes or hoses (see Fig. 14-25). These systems transfer heat more efficiently than forced air systems without the negative effects of exhaust gases and drying of the concrete from air movement. The specific heat of water/glycol solutions is more than six times greater than air. As a result, hydronic heaters can deliver very large quantities of heat at low temperature differentials of 5°C (10°F) or less between the heat transfer hose and the concrete. Cracking and curling induced by temperature gradients within the concrete are almost eliminated along with the danger of accidentally overheating the concrete and damaging long-term strength gain.

Typical applications for hydronic systems include thawing and preheating subgrades. They are also used to cure elevated and on-grade slabs, walls, foundations, and columns. To heat a concrete element, hydronic heating hoses are usually laid on or hung adjacent to the structure and covered with insulated blankets and sometimes plastic sheets. Usually, construction of temporary enclosures is not necessary. Hydronic systems can be used over areas much larger than would be practical to enclose. If a heated enclosure is necessary for other work, hydronic hoses can be sacrificed (left under a slab on grade) to make the slab a radiant heater for the structure built above (Grochoski 2000).

Any heater burning a fossil fuel produces carbon dioxide (CO₂); this gas will combine with calcium hydroxide on the surface of fresh concrete to form a weak layer of calcium carbonate that interferes with cement hydration (Kauer and Freeman 1955). The result is a soft, chalky surface that will dust under traffic. Depth and degree of carbonation depend on concentration of CO₂, curing temperature, humidity, porosity of the concrete, length of exposure, and method of curing. Direct-fired heaters, therefore, should not be permitted to heat the air over concreting operations—at least until 24 hours have elapsed. In addition, the use of gasoline-powered construction equipment should be restricted in enclosures during that time. If unvented heaters are used, immediate wet curing or the use of a curing compound will minimize carbonation.

Carbon monoxide (CO), another product of combustion, is not usually a problem unless the heater is using recirculated air. Four hours of exposure to 200 parts per million of CO will produce headaches and nausea. Three hours of exposure to 600 ppm can be fatal. The American National Standard Safety Requirements for Temporary and Portable Space Heating Devices and Equipment Used in the Construction Industry (ANSI A10.10) limits concentrations of CO to 50 ppm at worker breathing levels. The standard also establishes safety rules for ventilation and the stability, operation, fueling, and maintenance of heaters.
A salamander is an inexpensive combustion heater without a fan that discharges its combustion products into the surrounding air; heating is accomplished by radiation from its metal casing. Salamanders are fueled by coke, oil, wood, or liquid propane. They are but one form of a direct-fired heater. A primary disadvantage of salamanders is the high temperature of their metal casing, a definite fire hazard. Salamanders should be placed so that they will not overheat formwork or enclosure materials. When placed on floor slabs, they should be elevated to avoid scorching the concrete.

Some heaters burn more than one type of fuel. The approximate heat values of fuels are as follows:

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>Heat Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. 1 fuel oil</td>
<td>37,700 kJ/L (135,000 Btu/gal)</td>
</tr>
<tr>
<td>Kerosene</td>
<td>37,400 kJ/L (134,000 Btu/gal)</td>
</tr>
<tr>
<td>Gasoline</td>
<td>35,725 kJ/L (128,000 Btu/gal)</td>
</tr>
<tr>
<td>Liquid-propane gas</td>
<td>25,500 kJ/L (91,500 Btu/gal)</td>
</tr>
<tr>
<td>Natural gas</td>
<td>37,200 kJ/m³ (1,000 Btu/ft³)</td>
</tr>
</tbody>
</table>

The output rating of a portable heater is usually the heat content of the fuel consumed per hour. A rule of thumb is that about 134,000 kJ are required for each 100 m³ (36,000 Btu for 10,000 ft³) of air to develop a 10°C (20°F) temperature rise.

Electricity can also be used to cure concrete in winter. The use of large electric blankets equipped with thermostats is one method. The blankets can also be used to thaw subgrades or concrete foundations.

Use of electrical resistance wires that are cast into the concrete is another method. The power supplied is under 50 volts, and from 7.0 to 23.5 MJ (1.5 to 5 kilowatt-hours) of electricity per cubic meter (cubic yard) of concrete is required, depending on the circumstances. The method has been used in the Montreal, Quebec, area for many years. Where electrical resistance wires are used, insulation should be included during the initial setting period. If insulation is removed before the recommended time, the concrete should be covered with an impervious sheet and the power continued for the required time.

Steam is another source of heat for winter concreting. Live steam can be piped into an enclosure or supplied through radiant heating units. In choosing a heat source, it must be remembered that the concrete itself supplies heat through hydration of cement; this is often enough for curing needs if the heat can be retained within the concrete with insulation.

## DURATION OF HEATING

After concrete is in place, it should be protected and kept at the recommended temperatures listed on Line 4 of Table 14-1. These curing temperatures should be maintained until sufficient strength is gained to withstand exposure to low temperatures, anticipated environment, and construction and service loads. The length of protection required to accomplish this will depend on the cement type and amount, whether accelerating admixtures were used, and the loads that must be carried. Recommended minimum periods of protection are given in Table 14-3. The duration of heating structural concrete that requires the attainment of full service loading before forms and shores are removed should be based on the adequacy of in-place compressive strengths rather than an arbitrary time period. If no data are available, a conservative estimate of the length of time for heating and protection can be made using Table 14-3.

### Moist Curing

Strength gain stops when moisture required for curing is no longer available. Concrete retained in forms or covered with insulation seldom loses enough moisture at 5°C to 15°C (40°F to 55°F) to impair curing. However, a positive means of providing moist curing is needed to offset drying from low wintertime humidities and heaters used in enclosures during cold weather.

Live steam exhausted into an enclosure around the concrete is an excellent method of curing because it provides both heat and moisture. Steam is especially practical in extremely cold weather because the moisture provided offsets the rapid drying that occurs when very cold air is heated.

Liquid membrane-forming compounds can be used for early curing of concrete surfaces within heated enclosures.

### Terminating the Heating Period

Rapid cooling of concrete at the end of the heating period should be avoided. Sudden cooling of the concrete surface while the interior is still warm may cause thermal cracking, especially in massive sections such as bridge piers, abutments, dams, and large structural members; thus cooling should be gradual. A safe temperature differential between a concrete wall and the ambient air temperature can be obtained from ACI 306R-88. The maximum uniform drop in temperature throughout the first 24 hours after the end of protection should not be more than the amounts given in Table 14-2. Gradual cooling can be accomplished by lowering the heat or by simply shutting off the heat and allowing the enclosure to cool to outside ambient air temperature.

### FORM REMOVAL AND RESHORING

It is good practice in cold weather to leave forms in place as long as possible. Even within heated enclosures, forms serve to distribute heat more evenly and help prevent drying and local overheating.

If the curing temperatures listed on Line 4 of Table 14-1 are maintained, Table 14-3A can be used to determine the minimum time in days that vertical support for forms
should be left in place. Before shores and forms are removed, fully stressed structural concrete should be tested to determine if in-place strengths are adequate, rather than waiting an arbitrary time period. In-place strengths can be monitored using one of the following: (1) field-cured cylinders (ASTM C 31 or AASHTO T 23); (2) probe penetration tests (ASTM C 803); (3) cast-in-place cylinders (ASTM C 873); (4) pullout testing (ASTM C 900); or (5) maturity testing (ASTM C 1074). Many of these tests are indirect methods of measuring compressive strength; they require correlation in advance with standard cylinders before estimates of in-place strengths can be made.

If in-place compressive strengths are not documented, Table 14-3B lists conservative time periods in days to achieve various percentages of the standard laboratory-cured 28-day strength. The engineer issuing project drawings and specifications in cooperation with the formwork contractor must determine what percentage of the design strength is required (see ACI Committee 306). Side forms can be removed sooner than shoring and temporary falsework (ACI Committee 347).

MATURITY CONCEPT

The maturity concept is based on the principle that strength gain in concrete is a function of curing time and temperature. The maturity concept, as described in ACI 306R-88 and ASTM C 1074 can be used to evaluate strength development when the prescribed curing temperatures have not been maintained for the required time or when curing temperatures have fluctuated. The concept is expressed by the equation:

Metric:  \[ M = \sum (C + 10) \Delta t \]

Inch-Pound Units:  \[ M = \sum (F - 14) \Delta t \]

where
- \[ M \] = maturity factor
- \[ \sum \] = summation
- \[ C \] = concrete temperature, degrees Celsius
- \[ F \] = concrete temperature, degrees Fahrenheit
- \[ \Delta t \] = duration of curing at temperature C (F), usually in hours

The equation is based on the premise that concrete gains strength (that is, cement continues to hydrate) at temperatures as low as -10°C (14°F).

Before construction begins, a calibration curve is drawn plotting the relationship between compressive strength and the maturity factor for a series of test cylinders (of the particular concrete mixture proportions) cured in a laboratory and tested for strength at successive ages.

The maturity concept is not precise and has some limitations. But, the concept is useful in checking the curing of concrete and estimating strength in relation to time and temperature. It presumes that all other factors affecting concrete strength have been properly controlled.

With these limitations in mind, the maturity concept has gained greater acceptance for representing the compressive strength of the concrete for removal of shoring or opening a pavement to traffic; but it is no substitute for quality control and proper concreting practices (Malhotra 1974 and ACI Committee 347).

To monitor the strength development of concrete in place using the maturity concept, the following information must be available:

1. The strength-maturity relationship of the concrete used in the structure. The results of compressive strength tests at various ages on a series of cylinders made of a concrete similar to that used in the structure; this must be done to develop a strength-maturity curve. These cylinders are cured in a laboratory at 23°C ± 2°C (73°F ± 3°F).
2. A time-temperature record of the concrete in place. Temperature readings are obtained by placing expendable thermistors or thermocouples at varying depths in the concrete. The location giving the lowest values provides the series of temperature readings to be used in the computation (Fig. 14-26).

See ACI 306R-88 for sample calculations using the maturity concept.
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