| IN-LB | Inch-Pound Units |
| --- | --- |
| SI | International System of Units |

# Guide to Hot Weather Concreting

Reported by ACI Committee 305

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# Guide to Hot Weather Concreting



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# ACI 305R-20

# Guide to Hot Weather Concreting

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*Environmental factors, such as high ambient temperature, low humidity, high wind, or both low humidity and high wind, affect concrete properties and the construction operations of mixing, transporting, and placing of the concrete materials. This guide provides measures that can be taken to minimize the undesirable effects of these environmental factors and reduce the potential for serious problems.*

*This guide defines hot weather, discusses potential problems, and presents practices intended to minimize them. These practices include selecting materials and proportions, precooling ingredients, and batching. Other topics discussed include length of haul, consideration of concrete temperature as placed, facilities for handling concrete at the site, and, during the early curing period, placing and curing techniques, and appropriate testing and inspection procedures in hot weather conditions.*

*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:** air entrainment; cooling; curing; evaporation; high temperature; hot weather construction; plastic shrinkage; production methods; retempering; slump tests; water content.




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# CHAPTER 1—INTRODUCTION AND SCOPE

## 1.1—Introduction

Hot weather can create problems in delivery, mixing, placing, and curing hydraulic-cement concrete that can adversely affect the properties and serviceability of the concrete. Most of these problems relate to the increased rate of cement hydration at higher temperature and increased evaporation rate of moisture from the freshly mixed concrete. The rate of cement hydration depends on ambient and concrete temperature, cement composition and fineness, amount and type of supplementary cementitious materials, and admixtures used.

A maximum as-placed concrete temperature is often specified in an effort to control rate of setting, strength, durability, plastic shrinkage cracking, thermal cracking, and drying shrinkage. The placement of concrete in hot weather, however, is too complex to be dealt with by just setting a maximum as-placed or as-delivered concrete temperature. Concrete durability is defined as the ability of concrete to resist weathering action, chemical attack, abrasion, or other process of deterioration (ACI 201.2R). Generally, if concrete strengths are satisfactory and curing practices are sufficient to avoid undesirable drying of surfaces, the durability of hot weather concrete will not differ greatly from similar concrete placed at normal temperatures.

Where an acceptable record of field tests is not available, concrete proportions can be determined by trial batches (ACI 301 and 211.1). Trial batches should be made at temperatures anticipated in the work and mixed following one of the procedures described in 4.10. The concrete supplier is generally responsible for determining concrete proportions to produce the required quality of concrete unless specified otherwise.

If the initial 24-hour curing is at 100°F (38°C), the 28-day compressive strength of the test specimens may be 10 to 15 percent lower than if cured at the required ASTM C31/C31M curing temperature (Gaynor et al. 1985). If the cylinders are allowed to dry at early ages, strengths will be reduced even further (Cebeci 1987). Therefore, proper curing of the test specimens during hot weather is critical, and steps should be taken to ensure that the specified procedures are followed.

The effects of high air temperature and low relative humidity are more pronounced with increases in wind speed. The potential problems of hot weather concreting can occur at any time of the year, but generally occur during the summer season. Drying conditions can occur even at lower ambient temperatures, with slower set times, lower relative humidity, and wind, all of which are conducive to higher evaporation. Precautionary measures required on a windy, sunny day will be stricter than those required on a calm, humid day, even if air temperatures are identical.

## 1.2—Scope

This guide identifies problems associated with hot weather concreting and describes practices that alleviate these potential adverse effects. These practices include suggested preparations and procedures for use in general types of hot weather construction, such as pavements, bridges, and buildings either cast in place or precast. Temperature, volume changes, and cracking problems associated with mass concrete are treated more thoroughly in ACI 207.1R, 207.2R, and 224R.

# CHAPTER 2—NOTATION AND DEFINITIONS

## 2.1—Notation

$E$ = evaporation rate, lb/ft$^2$/h (kg/m$^2$/h)

$e_a$ = water vapor pressure in psi (mmHg) in the air surrounding the concrete obtained by multiplying the saturation vapor pressure at the temperature of the air surrounding the concrete by the relative humidity of the air. Air temperature and relative humidity are measured approximately 4 to 6 ft (1.2 to 1.8 m) above the concrete surface on the windward side and shielded from the sun's rays

$e_o$ = saturation water vapor pressure in psi (mmHg) in the air immediately over the concrete surface, at the concrete temperature.

$e_s$ = saturation vapor pressure, psi (kPa)

$r$ = relative humidity, percent

$T$ = temperature, °F (°C)
$T_a$ = air temperature, °F (°C)
$T_c$ = concrete (water surface) temperature, °F (°C)
$V$ = average wind speed in mph (km/h), measured at 20 in. (0.5 m) above the concrete surface
$W$ = mass of water evaporated in lb/ft$^2$ (kg/m$^2$) of water-covered surface per hour

## 2.2—Definitions

Refer to the latest version of ACI Concrete Terminology for a comprehensive list of definitions. Definitions provided herein complement that resource.

**hot weather**—one or a combination of the following conditions that tends to impair the quality of freshly mixed or hardened concrete by accelerating the rate of moisture loss and rate of cement hydration, or otherwise causing detrimental results: high ambient temperature; high concrete temperature; low relative humidity; and high wind speed.

# CHAPTER 3—POTENTIAL PROBLEMS AND PRACTICES

## 3.1—Potential problems in hot weather

Potential problems for concrete in the freshly mixed state include:

a) Increased water demand

b) Increased rate of slump loss and corresponding tendency to add water at the job site

c) Increased rate of setting, resulting in greater difficulty with handling, compacting, and finishing, and a greater risk of cold joints

d) Increased tendency for plastic shrinkage and thermal cracking

e) Increased difficulty in controlling entrained air content

Damage to concrete caused by hot weather can never be fully alleviated. Potential deficiencies to concrete in the hardened state can include:

a) Decreased strengths resulting from adding water to satisfy the higher water demand

b) Increased tendency for drying shrinkage if additional water was added to the concrete

c) Thermal cracking from either cooling of the overall structure, or from temperature differentials within the cross section of the member

d) Decreased durability resulting from cracking

e) Greater variability of surface appearance, such as cold joints or color differences, due to different rates of hydration or different water-cementitious materials ratios (*w/cm*)

## 3.2—Potential problems related to other factors

Other factors that should be considered along with climatic factors include:

a) Cements with different and increased rate of hydration

b) High-early-strength concrete, which may be proportioned with higher total cementitious content

c) Thin concrete sections with correspondingly greater percentages of steel, which may complicate placing and consolidation of concrete

d) Economic necessity to continue work in extremely hot weather

e) Use of shrinkage-compensating cement

## 3.3—Practices for hot weather concreting

Good judgment is necessary to select procedures that appropriately blend quality, economy, and practicability. The procedures selected will depend on type of construction, characteristics of the materials being used, and the experience of the local industry in dealing with high ambient temperature, high concrete temperatures, low relative humidity, and high wind speed.

The most serious difficulties occur when personnel placing the concrete lack experience in constructing under hot weather conditions or in doing the specific type of construction. Last-minute improvisations are rarely successful. Early preventive measures should be applied with the emphasis on materials evaluation, advanced planning and purchasing, and coordination of all phases of work. Planning in advance for hot weather involves development of an appropriate concrete mixture and a detailed plan for mixing, transporting, placing, protecting, curing, and testing of concrete. Precautions to avoid plastic shrinkage cracking are important. The potential for thermal cracking, either from overall volume changes or from internal restraint, should be anticipated, properly assessed, and mitigated.

Typical methods to minimize and to limit crack size and spacing include: proper use and timely installation of joints; increased amounts of reinforcing steel; and practical limits on concrete temperature. Some adjustments to concrete mixtures that have been successful in hot weather conditions include: using a reduced cement content; using a low-heat-of-hydration cement; the selection and dosage of appropriate chemical admixtures; the use of supplementary cementitious materials to replace cement; and the use of synthetic microfibers and macrofibers.

Developing a comprehensive plan and procedures for use in hot weather concreting conditions include the following practices and measures used to reduce or avoid the potential problems of hot weather concreting, as discussed in detail in Chapters 4 to 6:

a) Selecting concrete materials and proportions with satisfactory records in hot weather conditions or that have shown by testing to be satisfactory

b) Reducing and controlling the temperature of fresh concrete

c) Using a concrete mixture with sufficient workability that will permit rapid placement and effective consolidation

d) Minimizing the time to transport, place, consolidate, and finish the concrete

e) Scheduling of placing operations during times of the day or night when weather conditions are favorable

f) Protecting the concrete from moisture loss during placing and curing periods

g) Scheduling a preplacement conference to discuss the requirements of hot weather concreting

These suggestions are offered with the caveat that it may not be practical to implement any or all of them on a given

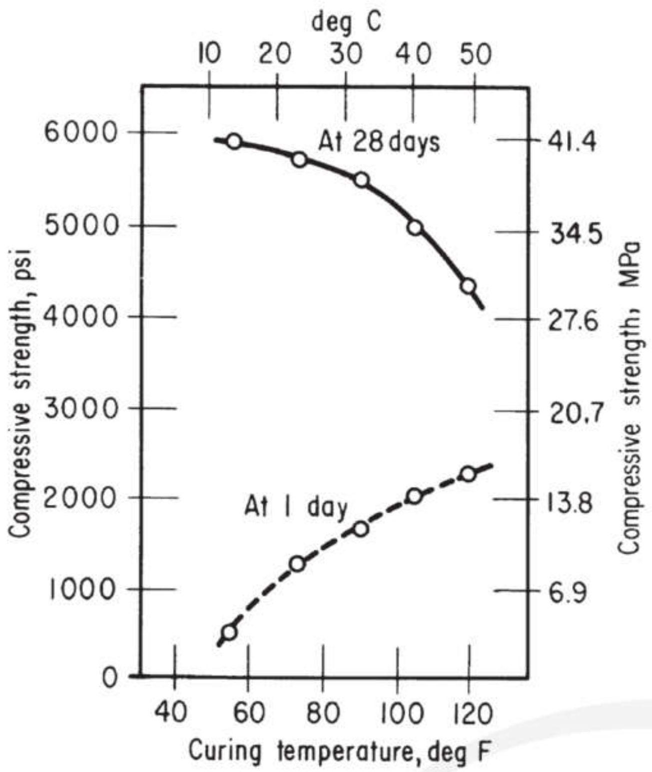


Fig. 4.1.1a—Effects of curing temperature on compressive strength of concrete (Verbeck and Helmuth 1968).

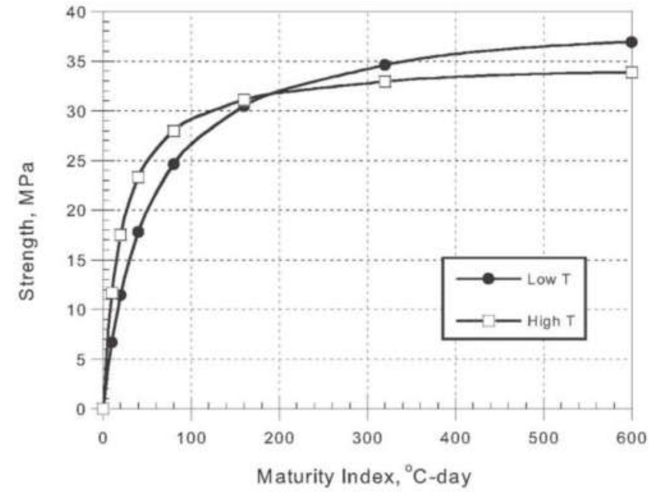


Fig. 4.1.1b—The crossover effect due to different early-age concrete temperature during development of the strength-maturity relationship (Carino and Lew 2001).

project. Each potential solution should be evaluated for its technical merits and economic cost-benefit ratio.

## CHAPTER 4—EFFECTS OF HOT WEATHER ON CONCRETE PROPERTIES

### 4.1—General

Properties of concrete that make it an excellent construction material can be adversely affected by hot weather. These properties include rate of setting; strength; permeability; dimensional stability; and resistance of the concrete to weathering, wear, and chemical attack. Achieving these properties depends on the proper selection and control of materials and mixture proportions; initial concrete temperature; wind speed; ambient temperature; and humidity condition during the placing and curing periods. Harmful effects of hot weather can be minimized by implementing procedures outlined in this guide.

**4.1.1** *Effect on strength*—Concrete mixed, placed, and cured at elevated temperatures normally develops higher early strengths than concrete produced and cured at lower temperatures, but strengths are generally lower at 28 days and later ages. This mechanical behavior of concrete has been called the crossover effect (Carino 1991). Figures 4.1.1a and 4.1.1b show that with increasing curing temperatures above 55°F (13°C), 1-day strength increases, and 28-day strength decreases (Klieger 1958; Verbeck and Helmuth 1968; Carino and Lew 2001). Some researchers conclude that a relatively more uniform microstructure of the hydrated cement paste can account for higher strength of concrete mixtures that cause rapid evaporation of surface water. The rate of



and cured at lower temperatures (Mehta 1986). At temperatures above 160°F (71°C), studies have shown reduction in compressive strength and increase in permeability with plain portland cement mixtures. This is possibly due to changes in rates of diffusion of the various ions during early hydration, and possible differences in the density of the calcium silicate hydrate (C-S-H) layer around the cement grains. Strength reductions and permeability increases were somewhat mitigated with supplementary cementitious materials (SCMs) such as fly ash or slag cement (Acquaye 2006). This reduction was due, in part, to a delay in the formation of ettringite.

**4.1.2** *Effect of proper curing of cylinders*—Laboratory tests have demonstrated the adverse effects of high temperatures with a lack of proper curing on concrete strength (Bloem 1954). The longer the delay between casting of the cylinders and placing them into standard moist storage, the greater the strength reduction. The data illustrate that inadequate curing combined with high placement temperatures impairs the hydration process and reduces strength. The tests were made on concrete without admixtures or SCMs that might have improved its performance at elevated temperatures. Other researchers determined that improper curing is more detrimental than high temperatures (Cebeci 1986), and that required strength levels can be maintained by the proper use of either chemical or mineral admixtures (Gaynor et al. 1985; Mittelacher 1985, 1992).

**4.1.3** *Effect of surface drying*—Plastic shrinkage cracking is frequently associated with hot weather concreting in arid climates. It occurs in exposed concrete, primarily in flatwork, but also in beams and footings. Plastic shrinkage can develop in other climates with cooler temperatures when the surface of freshly cast concrete dries and subsequently shrinks. Surface drying is initiated whenever the evaporation rate is greater than the rate at which moisture is provided to that surface by a combination of bleeding and initial curing measures such as fog-spraying. High concrete temperatures, high wind speed, low humidity, or a combination of these, can cause rapid evaporation of surface water. The rate of

**Table 4.1.4—Sample relationship between concrete temperatures and critical relative humidity**

| Concrete temperature, °F (°C) | Air temperature, °F (°C) | Evaporation rate | | | |
|---|---|---|---|---|---|
| | | 0.2 lb/ft$^2$/h (1.0 kg/m$^2$/h) | 0.15 lb/ft$^2$/h (0.75 kg/m$^2$/h) | 0.1 lb/ft$^2$/h (0.5 kg/m$^2$/h) | 0.05 lb/ft$^2$/h (0.25 kg/m$^2$/h) |
| | | Relative humidity, percent* | | | |
| 105 (41) | 95 (35) | 85 | 100 | 100 | 100 |
| 100 (38) | 90 (32) | 80 | 95 | 100 | 100 |
| 95 (35) | 85 (29) | 75 | 90 | 100 | 100 |
| 90 (32) | 80 (27) | 60 | 85 | 100 | 100 |
| 85 (29) | 75 (24) | 55 | 80 | 95 | 100 |
| 80 (27) | 70 (21) | 35 | 60 | 85 | 100 |
| 75 (24) | 65 (19) | 20 | 55 | 80 | 100 |

*Relative humidity, percent at which percent at evaporation rate will exceed the critical values shown, assuming air temperature is 10°F (6°C) cooler than the concrete temperature and a constant wind speed of 10 mph (16 km/h), measured at 20 in. (0.5 m) above the evaporating surface.

Note: Based on Fig. 4.1.1b; results rounded to nearest 5 percent.

bleeding, on the other hand, depends on concrete mixture ingredients and proportions, on the depth of the member being cast, and on the type of consolidation. Because surface drying is initiated when the evaporation rate exceeds the rate at which moisture supplied to the surface by bleeding and initial curing, the probability of plastic shrinkage cracking increases whenever the environmental conditions increase evaporation or when the concrete has a reduced bleeding rate. For example, concrete mixtures that incorporate fly ash, silica fume, or fine cements frequently have a low to negligible bleeding rate, making such mixtures highly sensitive to surface drying and plastic shrinkage, even under moderately evaporative conditions (ACI 234R).

**4.1.4** *Effect of evaporation*—Plastic shrinkage cracking is seldom a problem in hot and humid climates where relative humidity is rarely less than 80 percent. Table 4.1.4 shows, for various relative humidities, the concrete temperatures that may result in critical evaporation rate levels, and therefore increase the probability of plastic shrinkage cracking. The table is based on the assumption of a 10 mph (16 km/h) wind speed and an air temperature of 10°F (6°C) cooler than the concrete temperature.

Figure 4.1.4 is the NRMCA-PCA nomograph that is based on common hydrological methods for estimating the rate of evaporation of water from lakes and reservoirs, and is therefore the most accurate when estimating the rate of evaporation from the surface of concrete while that surface is covered with bleed water. When the concrete surface is not covered with bleed water, the nomograph and its underlying mathematical expression tends to overestimate the actual rate of water loss from the concrete surface by as much as a factor of 2 or more (Al-Fadhala and Hover 2001). The method is therefore most useful in estimating the evaporation potential of the ambient conditions and not as an estimator of the actual rate of water loss from the concrete. Early in the bleeding process, however, and at rates of evaporation less than or equal to 0.2 lb/ft$^2$/h (1.0 kg/m$^2$/h), the method has been shown to be as accurate for bleed-water evaporation as for hydrological water-pan evaporation (Al-Fadhala and Hover 2001) as long as the temperature, humidity, and wind speed were measured as described in Fig. 4.1.4.

It is critical that wind speed be monitored at 20 in. (0.5 m) above the evaporating surface because wind speed increases rapidly with height above the surface, and wind measurements taken from higher than the prescribed height used in developing the nomograph will overestimate evaporation rate. It should also be noted that wind speed varies tremendously over time, and estimates should not be based on transient gusts of wind. For these reasons, it is recommended that wind speed be averaged continuously over a period of not less than 10 minutes. Likewise, off-site measurements of wind speed from local weather stations or airports should not be used to characterize the evaporation potential of ambient conditions on the constructions site unless the evaporations estimate is being made for purely advisory purposes.

Figure 4.1.4 provides evaporation rate estimates based on environmental factors of temperature, humidity, and wind speed that contribute to rapid drying of recently-cast concrete surfaces, including plastic shrinkage cracking. The graphic method of the chart also yields ready information on the effect of changes in one or more of these factors. For example, it shows that concrete at a temperature of 70°F (21°C) placed at an air temperature of 70°F (21°C), with a relative humidity of 50 percent and a moderate wind speed of 10 mph (16 km/h), will have six times the evaporation rate of the same concrete placed when there is no wind.

For electronic-based applications, it may be more convenient to use the equations in 4.2 to calculate the estimated rate of surface moisture evaporation.

**4.1.5** *Effect of bleeding*—When evaporation rate is expected to approach the bleeding rate of the concrete, precautions should be taken, as explained in detail in Chapter 6. Because bleeding rates vary from zero to over 0.2 lb/ft$^2$/h (1.0 kg/m$^2$/h) over time and are not normally measured, it is common to assume a value for the critical rate of evaporation. The most commonly quoted value is 0.2 lb/ft$^2$/h (1.0 kg/m$^2$/h). More recent experience with bridge deck overlays containing silica fume has led to specified allowable evaporation rates of only 0.05 lb/ft$^2$/h (0.25 kg/m$^2$/h) (Virginia Department of Transportation 1997; Krauss and Rogalla 1996). Construction specifications for the State of New York and the City of Cincinnati assume intermediate

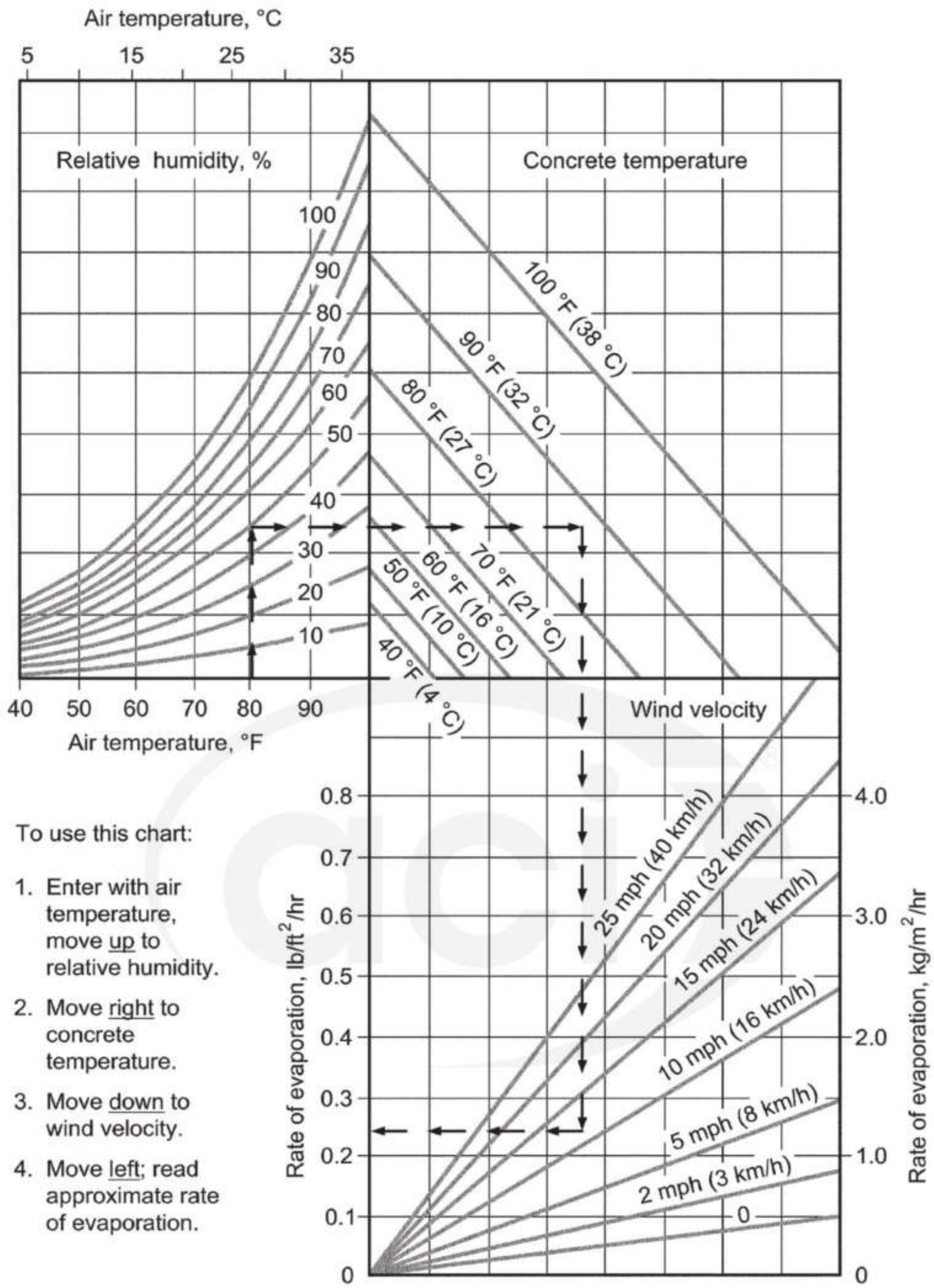


*Fig. 4.1.4—Effect of concrete and air temperatures, relative humidity, and wind speed on the rate of evaporation of surface moisture from concrete. This chart provides a graphic method of estimating the loss of surface moisture for various weather conditions. To use this chart, follow the four steps outlined in the figure. If the rate of evaporation approaches 0.2 lb/ft²/h (1 kg/m²/h), precautions against plastic shrinkage cracking are necessary (Lerch 1957). Wind speed is the average horizontal air or wind speed in mph (km/h) and should be measured at a level approximately 20 in. (0.5 m) higher than the evaporating surface. Air temperature and relative humidity should be measured at a level approximately 4 to 6 ft (1.2 to 1.8 m) higher than the evaporating surface on its windward side shielded from the sun's rays (Lerch 1957). Refer to 4.1.4 for additional information.*

evaporation rates of 0.15 and 0.10 lb/ft²/h (0.75 and 0.50 kg/m²/h), respectively. The probability for plastic shrinkage cracks to occur can be increased if the setting time of the concrete is delayed due to the use of slow-setting cement, an excessive dosage of retarding admixture, fly ash as a cement replacement, or cooled concrete. Fly ash is also likely to reduce bleeding and can thereby contribute to an increase in cracking tendency (ACI 232.2R). In such instances, it is prudent to extend the time where countermeasures are employed to reduce evaporative conditions above the concrete. These countermeasures may include the use of monomolecular films when applied to the bleed-water layer for the purpose of delaying, fogging, windbreaks, shading, and others as discussed in subsequent sections herein.

Plastic shrinkage cracks are difficult to close once they have occurred (refer to 6.3.4).

**4.1.6** *Effect on air entraining*—Increases in concrete temperature will generally reduce the amount of entrained air in the concrete. However, retempering may cause air content to increase and clustering of air around aggregate particles, as discussed in 4.8.6. Retempering beyond limits allowed by the concrete mixture design should generally be avoided for this reason.

## 4.2—Calculating estimated evaporation rate

The Menzel equation is used to quantify the severity of evaporative exposure. As documented by Uno (1998) and in more detail by Hover (2006), Menzel (1954) should be credited for finding the equation in the hydrologic literature and bringing it (exactly as he found it) to the attention of the concrete industry, changing only the units of measure for evaporation rate and wind speed. Kohler (1952, 1954) and Kohler et al. (1955) developed the equation on the basis of studies of the evaporation of water from Lake Hefner near Oklahoma City.

To use the Menzel equation, a value for the saturation vapor pressure of water at the temperature of the concrete is needed. This is the pressure exerted by water vapor at 100 percent relative humidity at temperature $T$, when $T$ is the same as the temperature of the concrete. The bleed water on the surface of the concrete evaporates, and the bleed-water temperature is assumed to be the same as the temperature of the concrete.

The Uno equation is used to determine the evaporation rate of moisture from the concrete surface. Uno (1998) combined Kohler's original equation with the saturated vapor pressure equations to produce a simplified and unified equation. The Uno equation uses information that can be directly obtained from field testing, such as air and concrete temperature, relative humidity of air, and wind speed.

Site conditions (air temperature, humidity, and wind speed) should be monitored to assess the need for evaporation control measures beginning no later than 1 hour before the start of concrete placing operations. Site conditions should be continually monitored at intervals of 30 minutes or less until the specified curing procedures have been applied.

It is critical that measurements of ambient conditions be taken as instructed below. This is because Kohler's evaporation equation was developed on the basis of air and water data collected in a precise manner. Further, it would generally be difficult to establish a reliable correlation between the ambient conditions of the job-site micro-climate and any off-site sources of weather data.

Equipment or instruments for measuring the rate of evaporation of surface moisture should be certified by the manufacturer or checked to be accurate within 1.8°F (1°C), within 5 percent relative humidity, and within 1 mph (1.6 km/h) wind speed, and should be used in accordance with the product manufacturer recommendations.

When the combination of the temperatures of air and concrete, relative humidity, and wind speed has the capacity to evaporate water from a free water surface at a rate equal to or greater than 0.2 lb/ft$^2$/h (1.0 kg/m$^2$/h), nearly all recently-cast concrete mixtures will be at risk of rapid, early drying and subsequent plastic shrinkage cracking. Under such conditions, this guide recommends that evaporation control measures are initiated. Many modern mixtures, particularly those proportioned for lower permeability, have a significantly reduced bleeding rate, and are consequently more vulnerable to plastic shrinkage cracking at lower evaporation rates. For such concretes, this guide considers the 0.2 lb/ft$^2$/h (1.0 kg/m$^2$/h) threshold to be unconservative.

**4.2.1** *Precision of calculating estimated evaporation rate*—The evaporation rate of Fig. 4.1.4 includes a built-in plot of the saturation water vapor pressure values. This is within the accuracy of the approximate nature of the measurements and the nature of the evaporation rate equation itself.

The user should note that the original research on which the Menzel and Uno equations are based was intended to estimate evaporation rate from exposed bodies of water over an extended period (months). The research showed reasonable accuracy over this period but showed significant variation (±38 percent at the 95 percent confidence level) between predicted and measured evaporation rate over any given 24-hour period. For hydrologists studying long-term trends within the context and accuracy of regional climate predictions, the precision of the equations was sufficient. However, the precision is not sufficient to evaluate compliance of evaporation rate of bleed water from concrete with a specification, or as the sole means of attributing distress such as cracking to plastic shrinkage. Instead, these equations should be used as a tool to generally indicate the need for implementing mitigation measures.

When it comes to specified values and issues of compliance versus noncompliance, it is recognized that an equation will provide a more precise result. The nomograph can be a quick and easy tool to assess conditions in the field but the user should be aware that the Menzel or Uno equations provide a precise result. In the ACI 305.1 specification, the Uno equation is the method specified to calculate estimated evaporation rate due to its ease-of-use and positive correlation to the Menzel equation.

The evaporation rate of surface moisture ($W$) can be determined by the Menzel equation as follows in Eq. (4.2.1)

$$W = 0.44(e_o - e_a)(0.253 + 0.096V) \quad \text{(in.-lb)}$$
$$W = 0.315(e_o - e_a)(0.253 + 0.060V) \quad \text{(SI)} \tag{4.2.1}$$

The saturated vapor pressure may be determined from tables, or from Eq. (4.2.2a), which are discussed further in 4.2.2.

**4.2.2** *Uno equation*—Uno (1998) reported a reliable equation for saturation vapor pressure of water in air as follows:

$$e_s = 0.0885 \cdot e^{\frac{17.3(T-32)}{395.1+T}} \quad \text{(in.-lb)} \tag{4.2.2a}$$
$$e_s = 0.61 \cdot e^{\frac{17.3T}{237.3+T}} \quad \text{(SI)}$$

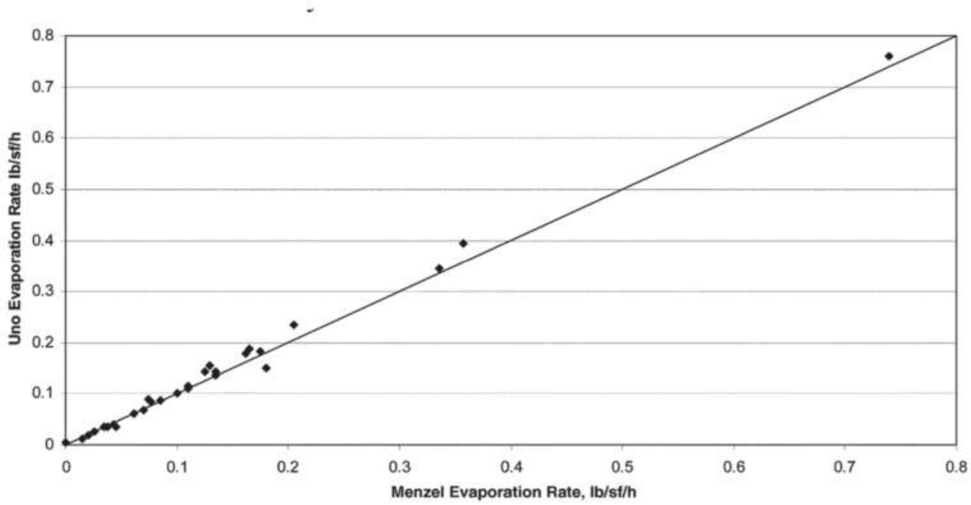


*Fig. 4.2.2—Comparison of Menzel formula to Uno equation (Uno 1998).*

Equation (4.2.2a) has been around since the early twentieth century and are used by the World Meteorological Organization (Tetens 1930; Murray 1967; Dilley 1968; Mills 1975). The results from the in.-lb unit equation were compared with the result from the present ACI vapor pressure table, as shown in Fig. 4.1.4. The two curves are indistinguishable, and on average, there is less than 0.3 percent difference between the table values and the equation. Given that the table values were interpolated, converted, and rounded, it cannot be said that the table values are more accurate. Uno (1998) identified the vapor pressure equations above and combined them with Kohler's original equation to produce a unified equation that takes vapor pressure into account

$$E = (T_c^{2.5} - r \cdot T_a^{2.5})(1 + 0.4V) \times 10^{-6} \quad \text{(in.-lb)} \tag{4.2.2b}$$

$$E = 5([T_c + 18]^{2.5} - r \cdot [T_a + 18]^{2.5})(V + 4) \times 10^{-6} \quad \text{(SI)}$$

Uno (1998) presented a table that compares the final, predicted evaporation rate computed by the newer equation and by Menzel for a wide range of differing ambient conditions. The results are shown in Fig. 4.2.2, where the line $x = y$ is shown for reference. Given the much greater variability in the measured input data and the approximate nature of the calculation as documented by Al-Fadhala and Hover (2001), the Uno version is satisfactory and its use is recommended.

**4.2.3** *Example of the Uno equation*—The Uno equation combines vapor pressure equations and the Menzel formula to provide a unified equation that takes vapor pressure into account. The Uno equation is included in ACI 305.1. The modified NRMCA Nomograph for Estimated Surface Evaporation Rates is intended as a graphical guide to determine an approximate solution of the Menzel formula. The nomograph is intended only to assist in field estimations of surface evaporation rates and does not replace the Uno equation for meeting the requirements of Section 3.1.3 of ACI 305.1-14.

**Example (U.S. Customary units):**

*Given:*

Concrete temperature ($T_c$) = 95°F

Air temperature ($T_a$) = 104°F

Wind speed ($V$) = 12 mph

Relative humidity ($r$) = 50 percent

Solve for evaporation rate ($E$)

$E = (T_c^{2.5} - rT_a^{2.5})(1 + 0.4V) \times 10^{-6}$

$E = (95^{2.5} - 0.5 \cdot 104^{2.5})(1 + 0.4 \cdot 12) \times 10^{-6} = 0.19$ lb/ft²/h

In this example, 0.19 lb/ft²/h is less than the specified evaporation rate of free surface water of 0.20 lb/ft²/h, as listed in 4.2. This example would indicate that, although the evaporation rate is approaching the specified limit, measures to reduce the evaporation rate would not be required by specification. For some mixtures, however, this evaporation rate could result in plastic shrinkage cracking, which is why the Architect/Engineer may select a lower specified value; for example, 0.15 lb/ft²/h, in accordance with the Optional Requirements Checklist of ACI 305.1-14.

**Example (SI units):**

*Given:*

Concrete temperature ($T_c$) = 35°C

Air temperature ($T_a$) = 40°C

Windspeed ($V$) = 20 km/h

Relative humidity ($r$) = 50 percent

Solve for evaporation rate ($E$)

$E = 5[(T_c + 18)^{2.5} - r(T_a + 18)^{2.5}](V + 4) \times 10^{-6}$

$E = 5[(35 + 18)^{2.5} - 0.5(40 + 18)^{2.5}](20 + 4) \times 10^{-6} = 0.92$ kg/m²/h

In this example, 0.92 kg/m²/h is less than the specified evaporation rate of free surface water of 1.00 kg/m²/h, as listed in 4.2. This example would indicate that, although the evaporation rate is approaching the specified limit, measures to reduce the evaporation rate would not be required by specification. For some mixtures, however, this evaporation rate could result in plastic shrinkage cracking, which is why the Architect/Engineer may select a lower specified value, for example 0.75 kg/m²/h, in accordance with the Optional Requirements Checklist of ACI 305.1-14.


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**4.2.3** *Fluid mechanics-based approach for estimating evaporation rate*—Fluid mechanics-based approaches can be employed for analyzing and estimating evaporation rate based on the boundary layer theory, mass transfer, diffusion, and convection (Bakhshi et al. 2012). These models are valid for the prediction of the evaporation rate from the bleed water on the surface of concrete during early stages of drying. These models are based on the case of evaporation that is controlled by the diffusion of the water vapor through the boundary layer covering the surface bleed water.

Parametric studies on these models reveal similar effects of the temperature, the relative humidity, and the wind velocity on the evaporation rate as Menzel equation (Fig. 4.1.1b). Additionally, these models can capture the effect of the size of the surface in the direction of wind flow on evaporation rates. As a result, reduction of evaporation rate has been predicted in these models by increasing characteristic length of evaporation. Verification of such approaches has been proved by results of most recent experimental data (Slowik et al. 2008; Azenha et al. 2007a,b; Lura et al. 2007; Hammer 2001). Assuming surface cooling occurrence, fluid mechanics-based models can also predict the evaporation rates with a good accuracy and within 0 to 30 percent of experimental results (Bakhshi et al. 2012).

## 4.3—Effects of temperature of concrete

Unless measures are taken to control concrete performance at elevated temperatures by the selection of suitable means, and concrete materials and proportions, as outlined in 4.4 through 4.10, increases in concrete temperature will have the following adverse effects:

a) Rate of hydration of the cement is increased, which reduces the time of setting and increases the difficulty to control fresh concrete properties prior to placement

b) The amount of the water required to produce a given slump increases with the time and temperature, as shown in Fig. 4.3a and 4.3b

c) Increased water content creates a decrease in strength and an increase in permeability and drying shrinkage

d) Slump loss is evident earlier after initial mixing and at a more rapid rate, and can cause difficulties with handling and placing operations

e) In a dry, windy climate, plastic shrinkage cracks are more probable

f) In sections of large dimensions, there is an increased rate of hydration and heat evolution that increases the difference in temperature between the interior and the exterior concrete. This can cause thermal cracking (ACI 207.1R)

g) Application of early curing methods is critical; a lack of proper curing is increasingly detrimental as temperatures rise

## 4.4—Maximum ambient and concrete temperature

Generally, in hot weather construction it is impractical to recommend a single maximum ambient or concrete temperature; for example, if the humidity is high and the wind speed is low, higher ambient and concrete temperatures can be permitted. A maximum ambient or concrete temperature appropriate for one application may be unrealistic for another.

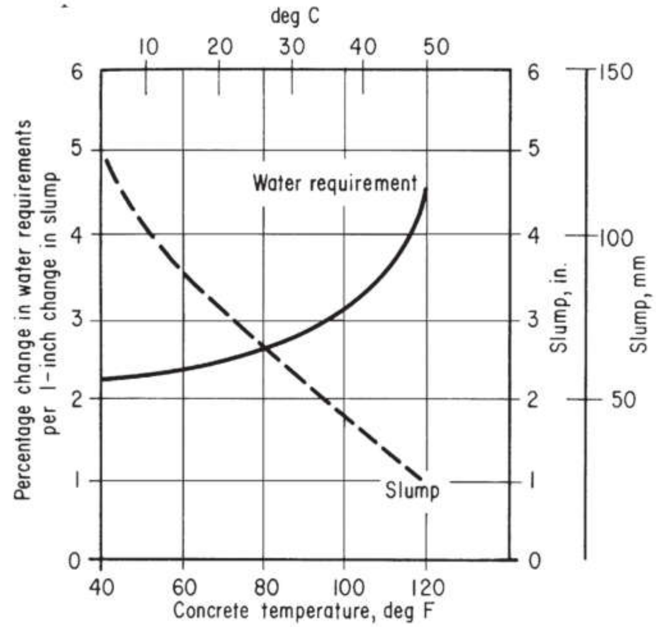


*Fig. 4.3a—Effect of concrete temperature on slump and on water required to change slump (average data for Type I and Type II cements) (Klieger 1958).*

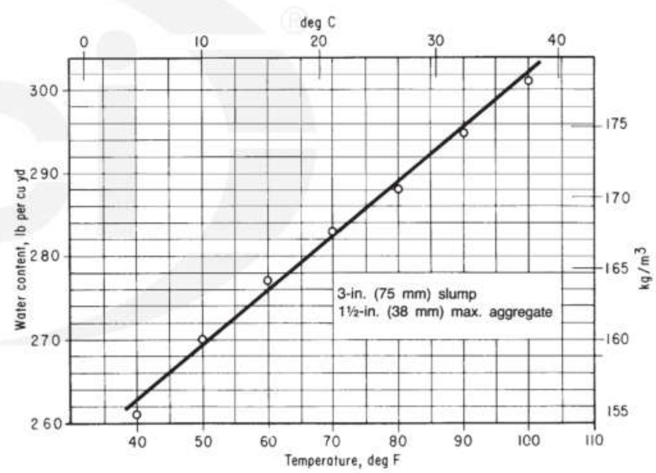


*Fig. 4.3b—Effect of temperature increase on water requirement of concrete (U.S. Bureau of Reclamation 1975).*

Accordingly, the committee can only provide information about the effects of higher temperatures in concrete as mentioned in 3.1 and 4.3, and advise that at some concrete placement temperature between approximately 75 and 100°F (24 and 38°C) there is a limit that will be found to be most favorable for best results in each hot weather operation, and such a limit should be determined for the work.

It is recommended that the job specifications allow for flexibility in setting the maximum concrete placement temperature, based on both engineering requirements and practical limitations. This is important because cooling of concrete to an excessively low temperature limit can require the removal of a large amount of heat from the concrete such as through ice or liquid nitrogen. This cooling is very expensive in terms of both energy and cost, and should not be required unnecessarily. Chapter 5 discusses cooling

measures in further detail. Hot weather concreting should be discussed during the preplacement conference and written procedures should be submitted by the contractor.

Trial batches of concrete for the job should be made at the limiting temperature selected, or at the expected job site high temperature, rather than the 68 to 86°F (20 to 30°C) range given in ASTM C192/C192M. On critical projects with mixture designs containing ingredients that reduce bleeding, it has been prudent to complement preplacement conferences with a trial or mockup placement. This is especially beneficial for finishing crews unfamiliar with specialty mixtures and to demonstrate the importance of countermeasures in protecting the fresh concrete in hot weather and critical need for immediate curing. Procedures for testing of concrete batches at temperatures higher than approximately 70°F (21°C) are given in 4.10.

## 4.5—Water

Water, as an ingredient of concrete, greatly influences many of its significant properties, both in the freshly mixed and hardened state. High water temperatures cause higher concrete temperatures, and as the concrete temperature increases, more water is needed to obtain the same slump. Figure 4.3b illustrates the effect of concrete temperature on water requirements to maintain slump. The extra water increases the *w/cm* and will decrease the strength, increase the drying shrinkage and permeability, thus reducing durability, and will affect other related properties of the concrete. These effects should be accounted for during mixture proportioning. Although pertinent to concrete placed under all conditions, there is an increased need to limit the use of additional water in concrete placed under hot weather conditions (4.3).

**4.5.1** *Effect on slump*—Figure 4.3a illustrates the general effects of increasing concrete temperature on slump of concrete when the amount of mixing water is held constant. It indicates that an increase of 20°F (11°C) in temperature can be expected to decrease the slump by approximately 1 in. (25 mm). Figure 4.3a also illustrates changes in water requirements necessary to produce a 1 in. (25 mm) increase in slump at various temperature levels. For 70°F (21°C) concrete, approximately 2.5 percent more water is required to increase slump 1 in. (25 mm); for 120°F (49°C) concrete, 4.5 percent more water is needed for the 1 in. (25 mm) slump increase. The mixing water required to change slump will be less when a water-reducing, mid-range water-reducing, or high-range water-reducing admixture is properly used.

**4.5.2** *Effect on drying shrinkage*—Drying shrinkage generally increases with total water content (Portland Cement Association 1992). Rapid slump loss in hot weather often increases the demand for water, increasing total water content and, therefore, increasing the potential for subsequent drying shrinkage. Concrete cast in hot weather is also susceptible to thermal shrinkage as it subsequently cools. The combined thermal and drying shrinkage can lead to more cracking than observed for the same concrete placed under milder conditions.

**4.5.3** *Effect on temperature of concrete*—Because water has a specific heat of approximately four to five times that of cement or aggregates, the temperature of the mixing water has the greatest effect per unit weight on the temperature of concrete, even though water is used in smaller quantities than the other ingredients. For most concrete, chilled water can reduce the concrete placing temperature, usually by a maximum of approximately 8°F (4.4°C) (Fig. 4.5.3a). In general, lowering the temperature of the batch water by 3.5 to 4°F (1.9 to 2.2°C) will reduce the concrete temperature approximately 1°F (0.5°C), but the quantity of cooled water should not exceed the batch water requirement, which will depend on the mixture proportions and the moisture content of aggregates. Efforts should therefore be made to obtain cold water. Water can be cooled to as low as 33°F (1°C) using water chillers, ice, heat pump technology, or liquid nitrogen. To keep it cold, tanks, pipes, and trucks used for storing or transporting water should be insulated and painted white.

Using ice as part of the mixing water is a common measure used to reduce concrete temperature. On melting, ice absorbs heat at the rate of 144 Btu/lb (335 J/g). To be most effective, the ice should be crushed, shaved, or chipped when placed directly into the mixer as part of the mixing water; the ice should not be allowed to melt before it is placed in the mixer in contact with other ingredients, but it should melt completely before concrete mixing is complete. Crushed ice should be stored at a temperature that will prevent lumps from forming by refreezing of particles.

For a more rapid blending of materials at the beginning of mixing, only part of the available batch water should be added in the form of ice. Its quantity is usually limited to approximately 75 percent of the batch water requirement, less for low-water-content mixtures. To maximize amounts of ice or cold mixing water, aggregates should be well drained of free moisture, permitting a greater quantity of ice or cold mixing water to be used. Figure 4.5.3b illustrates

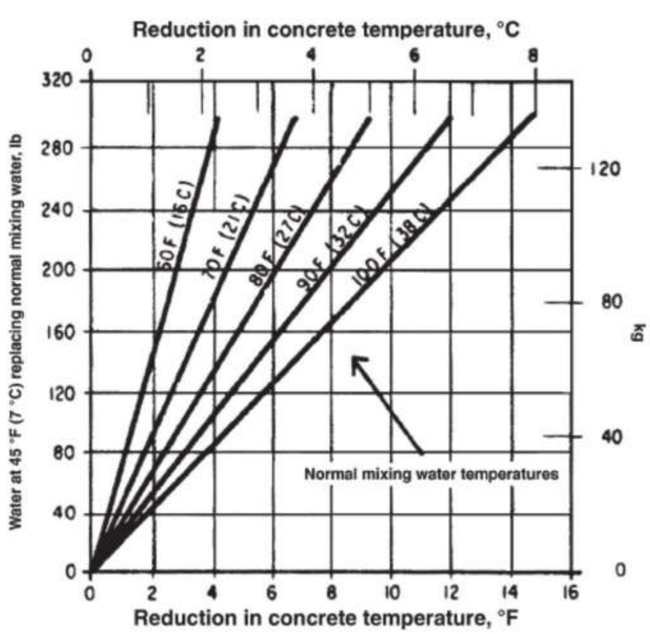


*Fig. 4.5.3a—General effects of cooled mixing water on concrete temperature (NRMCA 1962).*

potential reductions in concrete temperature by substituting varying amounts of ice at 32°F (0°C) for mixing water at the temperatures shown. Mixing should be continued until the ice has melted completely.

The amount of ice that can be added to the mixture has practical limits based on the batching requirements. For example, the use of ice can affect the efficacy of chemical admixtures, because less liquid water will be available at the beginning of mixing. Mixtures with low water contents generally require mid-range or high-range water reducers to achieve the desired consistency. Such mixtures will not perform properly if too much of the batch water is replaced with ice.

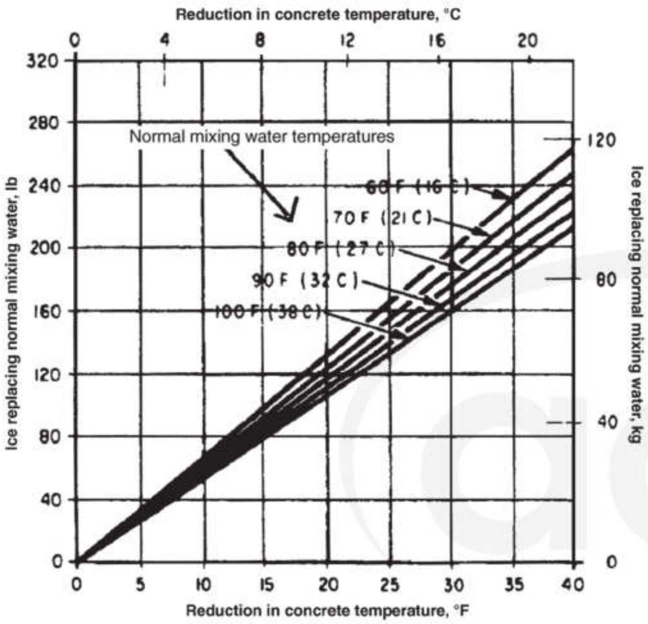


*Fig. 4.5.3b—General effects of ice in mixing water on concrete temperature. Temperatures are normal mixing water temperatures (NRMCA 1962).*

Temperature reduction by adding ice can also be estimated by using Eq. (A.2a) or (A.2b) in Appendix A. For most concrete, the maximum temperature reduction with ice is approximately 20°F (11°C).

When greater temperature reductions are required, cooling by injection of liquid nitrogen into the mixer holding mixed concrete can be the most expedient means (Appendix B). Injected liquid nitrogen does not affect the mixing water requirement except by reducing concrete temperature.

## 4.6—Cement

High concrete temperature increases the rate of hydration (Fig. 4.6). As a result, concrete stiffens more rapidly and requires more water to produce or maintain the desired slump unless offset by measures described in 4.7 and 4.8. The higher water content will cause strength loss and increase the tendency of the concrete to crack.

**4.6.1** *Effect of slow-setting cement*—Selection of a particular cement can have a decided effect on the hot weather performance of concrete, as illustrated in Fig. 4.6. Although the curves are based on limited data from mixtures that use different cements in combination with a set-retarding admixture, they show, for example, that when tested at 100°F (38°C), the concrete with the slowest-setting cement reaches time of final setting 2-1/2 hours later than the concrete with the fastest-setting cement. The concrete that sets slowest at 100°F (38°C) was the fastest-setting cement when tested at 50°F (10°C). Figure 4.6 illustrates the difficulty of predicting concrete performance at different temperatures.

The use of a slower-setting Type II portland cement (ASTM C150/C150M), moderate heat (MH) (ASTM C1157/C1157M) or Type IP or IS blended cement (ASTM C595/C595M) can improve the handling characteristics of concrete in hot weather (ACI 225R). Concrete that contains the slower-setting cements is more likely to exhibit plastic shrinkage cracking, if not protected.

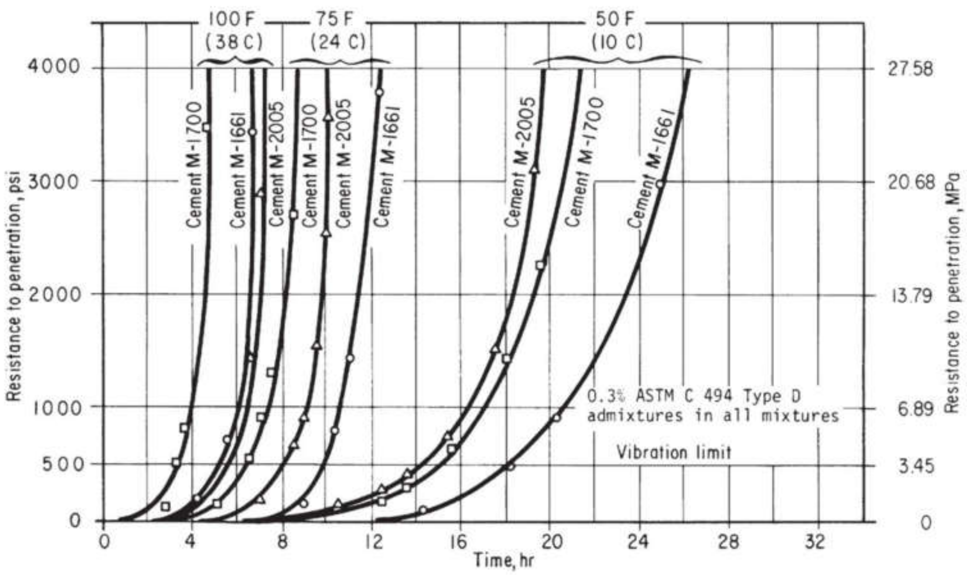


*Fig 4.6—Effect of temperature and brand of cement on setting time characteristics of concrete mortars (Tuthill and Cordon 1955).*


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Practically, it can be difficult or prohibitively expensive to specify a slow-setting cement due to supplier restrictions, material availability, and cost. Suppliers will often produce a cement that meets requirements for several ASTM cement types, such as Type I and Type II; or Type II and Type V. Concrete suppliers often have only a few economical choices of cement sources that are locally available. A special request for slow-setting cement is often uneconomical due to higher transportation costs.

When using slower-hydrating cements, the slower rate of heat development and the simultaneous dissipation of heat from the concrete result in lower peak temperatures. There is less thermal expansion, and the risk of thermal cracking upon cooling of the concrete is reduced. This is an important consideration for slabs, walls, and mass concretes, as discussed in ACI 207.1R and 207.2R. The temperature increase from hydration of cement in a given concrete mixture is proportional to its cement content. Therefore, the cement content should be limited to the amount required to provide strength and durability.

Concrete mixtures that obtain high strength at an early age will develop high concrete temperature during initial curing. Thermal protection should be provided for high-strength concrete mixtures to ensure gradual cooling at a rate that will not cause them to crack (6.4.1).

Cement is sometimes delivered at relatively high temperatures. This is not unusual for newly manufactured cement that has not had an opportunity to cool after grinding of the component materials. Concrete mixtures consist of approximately 10 to 15 percent cement; thus, the concrete temperature will increase approximately 1°F (0.5°C) for each 8°F (4°C) increase in cement temperature.

## 4.7—Supplementary cementitious materials

Materials in this category include fly ash and other pozzolans (ASTM C618) and slag cement (ASTM C989/C989M). Use of concrete containing supplementary cementitious materials (SCMs), in particular silica fume, should be evaluated when hot weather conditions exist due to its lower bleeding rate, which can pose a risk for potential shrinkage and cracking if adequate protection and curing are not in place. It is a good practice to have a comprehensive plan to protect and cure the concrete in hot weather conditions, especially when using SCMs. Fly ash and slag are widely used as partial replacements for portland cement; in general, they can impart a slower rate of setting and of early strength gain to the concrete, as explained in 4.6.1. Faster-setting cements or cements that cause rapid slump loss in hot weather can perform satisfactorily in combination with these materials (Gaynor et al. 1985). The use of fly ash can reduce the rate of slump loss of concrete under hot weather conditions (Ravina 1984; Gaynor et al. 1985). Class F fly ash is better than Class C fly ash to reduce the rate of slump loss.

Some concrete mixtures containing Class C fly ash or with up to 50 percent slag cement, especially Grade 120 slag, can generate heat at a rate similar to 100 percent portland cement mixtures. Concrete mixtures with some Class C fly ashes and slag cements can have significant setting problems when combined with certain chemical admixtures, especially in the presence of under-sulfated cements (Sandberg and Roberts 2005). Such problems are caused by depletion of sulfate in the mixture and can be exacerbated at high temperatures because additional chemical admixtures are added to the mixture to maintain workability. It is recommended that systems with high percentages of SCMs be evaluated prior to placement.

## 4.8—Chemical admixtures

Various types of chemical admixtures (ASTM C494/C494M) were found to be beneficial in offsetting some of the undesirable characteristics of concrete placed during periods of high ambient temperatures (refer also to ACI 212.3R). The benefits can include lower mixing water demand, extended periods of use, and strengths comparable with, or higher than, concrete without admixtures placed at lower temperatures. Their effectiveness depends on the chemical reactions of the cement used in the concrete. Admixtures without a history of satisfactory performance at the expected hot weather conditions should be evaluated before their use.

**4.8.1** *Water-reducing and retarding admixtures*—Retarding admixtures meeting ASTM C494/C494M Type D requirements have both water-reducing and set-retarding properties, and are used widely under hot weather conditions. They can be included in concrete in varying proportions and in combination with other admixtures so that, as temperature increases, higher dosages of the admixture can be used to obtain a uniform time of setting. Their water-reducing properties largely offset the higher water demand that results from increases in concrete temperature. Because water-reducing and retarding admixtures generally increase concrete strength, they can be used, with proper mixture adjustments, to avoid strength losses that would otherwise result from high concrete temperatures (Gaynor et al. 1985; Mittelacher 1985, 1992). Compared with concrete without admixtures, a concrete mixture that uses a water-reducing and retarding admixture can have a higher rate of slump loss. The net water reduction and other benefits remain substantial even after the initial slump is adjusted to compensate for slump loss.

Hydroxylated carboxylic acid (ACI 212.3R-16 Section 4.2.2, Category 3) and some admixtures meeting ASTM C494/C494M Type D requirements can increase the early bleeding and rate of bleeding of concrete. This admixture-induced early bleeding can be helpful in preventing drying of the surface of concrete placed at high ambient temperature and low humidity. Concrete that is prone to bleeding should generally be reconsolidated after most of the bleeding has taken place. Otherwise, differential settling can occur, which can lead to cracks over reinforcing steel and other inserts in near-surface locations. This cracking is more likely in cool weather with slower-setting concretes than in hot weather. If the admixture reduces the tensile strength and tensile strain capacity, however, plastic shrinkage tendencies can be increased (Ravina and Shalon 1968a,b). Other admixtures (ACI 212.3R-16 Section 4.2.2, Categories 1 and 2) can reduce bleeding rate. If drying conditions are such

that surface crusting inhibits bleed water from reaching the surface, trapped bleed water accumulating beneath a crusted surface can contribute to surface delaminations. Under such conditions, fog sprays, evaporation retardants (materials that retard the evaporation of bleeding water of concrete), or both, should be used to prevent crusting, and finishing operations should be adjusted to minimize damaging the quality of the surface.

**4.8.2** *Flowing concrete*—Some high-range, water-reducing and retarding admixtures (ASTM C494/C494M, Type G), and water-reducing and retarding admixtures (ASTM C494/C494M, Type D) can provide significant benefits under hot weather conditions when used to produce flowing concrete. At higher slumps, heat gain from internal friction during mixing of the concrete will be less (ASTM International 1994; ACI 207.4R). The improved handling characteristics of flowing concrete permit more rapid placement and consolidation, and the period between mixing and initial finishing can therefore be reduced. The rate of slump loss of flowing concrete can also be less at higher temperatures than in concrete using conventional retarders (Yamamoto and Kobayashi 1986). Concrete strengths are generally found to be substantially higher than those of comparable concrete without admixtures and with the same cement content. Certain products can cause significant bleeding, which can be beneficial, but can also require some precautions (4.8.1). Air-content tests are needed before placement to assure compliance of specified air content. Assurance that the air-void system is not impaired can be determined by a hardened air analysis or ASTM C666/C666M freezing-and-thawing testing.

**4.8.3** *Extended slump*—Some high-range water-reducing retarders can maintain the necessary slump for extended periods at elevated concrete temperatures (Collepardi et al. 1979; Hampton 1981; Guennewig 1988). Some mixtures requiring slump for extended periods can also benefit from the delaying the addition of high-range water-reducing admixture at the job site. These will be of particular benefit in delayed placements or deliveries over greater distances. Other high-range water-reducing admixtures can greatly accelerate slump loss, particularly when initial slumps are less than 3 to 4 in. (75 to 100 mm). Some water-reducing admixtures can cause the concrete to extend its working time by up to 2 hours, followed by acceleration of strength gain.

**4.8.4** *Mid-range water-reducing admixtures*—Since the early 1990s, the use of mid-range water-reducing admixtures in hot weather has increased. Mid-range water-reducing admixtures provide up to 15 percent water reduction, which is higher than conventional water-reducing admixtures, but has lower water reduction than high-range water-reducing admixtures. Although at present there is no ASTM classification, mid-range water-reducing admixtures comply with the requirements of ASTM C494/C494M Type A admixtures and, in some cases, Type F admixtures. These admixtures should not significantly delay the setting time of the concrete. At higher dosages, conventional water-reducing admixtures can achieve this water reduction, but with a significant increase in the setting time of the concrete. The pumping and finishing characteristics of concrete containing mid-range water-reducing admixtures are improved when compared with concrete containing conventional Type A water-reducing admixtures. The use of mid-range water-reducing admixtures is particularly beneficial in cases where aggregate properties contribute to poor workability or finishing difficulties. The surface appearance of concrete containing a mid-range water-reducing admixture could be changed, thereby requiring a change in the timing of finishing operations. Mid-range water-reducing and retarding admixtures that comply with ASTM C494/C494M requirements for Type D admixtures are also available.

**4.8.5** *Extended set-control admixtures*—The use of extended set-control admixtures to stop the hydration process of freshly mixed concrete (freshly batched or returned fresh concrete that normally would be disposed) and concrete residue (wash water) in concrete truck drums has gained increased acceptance in hot weather environments since their introduction in 1986. Some extended set-control admixtures comply with ASTM C494/C494M requirements for Type B retarding admixtures and Type D water-reducing and retarding admixtures. Extended set-control admixtures differ from conventional retarding admixtures in that they stop the hydration process of both the silicate and aluminate phases in portland cement. Regular retarding admixtures act only on the silicate phases, which extend, but do not stop, the hydration process. The technology of extended set-control admixtures can also be used to stop the hydration process of freshly batched concrete for hauls requiring extended time periods or slow placement methods during transit. For this application, the extended set-control admixture is added during or immediately after the batching process. Proper dosage rates of extended set-control admixtures should be determined by trial mixtures that incorporate project time requirements in this way, ensuring that the concrete will achieve the required setting time. Additional admixtures are not required to restart hydration.

**4.8.6** *Air-entraining admixtures*—Increases in concrete temperature will generally reduce the amount of entrained air in the concrete. Additional air-entraining admixture may be needed; however, other admixtures such as polycarboxylate-based high-range water-reducing admixtures may increase air content in the concrete as well. High concrete temperatures, in isolation, are not known to increase air entrainment of concrete. However, water sometimes is added to the concrete (retempering) in these situations due to loss of workability. Retempering will cause air content to increase and clustering of air around aggregate particles may be observed (Kozikowski et al. 2005). Retempering of concrete is not a good practice because it can cause strength problems and thus should be discouraged.

**4.8.7** *Newer admixture formulations*—In general, newer formulations of water-reducing admixtures, such as polycarboxylate-based high-range water-reducing admixtures, maintain workability and slump better than older formulations (for example, naphthalene and melamine-based high-range water-reducing admixtures). Such admixtures are commonly used in hot weather applications. Care should be

taken to evaluate the admixtures for their effects on entrained air in a mixture.

**4.8.8** *Evaluation*—The qualifying requirements of ASTM C494/C494M provide a valuable screening procedure for the selection of admixture products. Admixtures without a performance history that pertain to the concrete material selected for the work should first be evaluated in laboratory trial batches at the expected high job temperature using one of the procedures described in 4.10. Some high-range water-reducing retarders cannot demonstrate their potential benefits when used in small laboratory batches. Further testing may then be required in production-size concrete batches. During preliminary field use, concrete containing an admixture should be evaluated for consistency of performance regarding the desired characteristics in hot weather construction. When evaluating admixtures, properties such as workability, pumpability, early strength development, placing and finishing characteristics, appearance, and effect on reuse of molds and forms should be considered in addition to the basic properties of slump retention, setting time, and strength. These characteristics can influence selection of an admixture and its dosage more than properties usually covered by most specifications.

## 4.9—Aggregates

Aggregates, the major constituent of concrete, usually account for 60 to 80 percent of the volume of normalweight concrete. Therefore, the properties of the aggregate affect the quality of concrete significantly. The three principal factors that affect the amount of water required to produce concrete at a given slump are gradation, particle shape, and the absence of undersized material (ACI 221R). Crushed coarse aggregate contributes to higher water demand than rounded gravels but may provide better resistance to cracking (ACI 224R), provided coefficient of thermal expansion and elastic modulus are low.

Coarse aggregate is the ingredient with the greatest mass in concrete; therefore, changes in its temperature have a considerable effect on concrete temperatures. For example, a moderate 1.5 to 2°F (0.8 to 1.1°C) temperature reduction of aggregate will lower the concrete temperature by 1°F (0.5°C). Cooling the coarse aggregate can be an effective supplementary means to achieve desired lower concrete temperature (Appendix B).

## 4.10—Fibers

Use of fibers, even at relatively low fiber volume, is an effective method to control cracking of plastic concrete (ACI 224.1R; ACI 302.1R). Addition of fibers increases the strength and strain capacity during the very early ages (up to 12 hours) to minimize the potential for cracking under the tensile stresses generated by the shrinkage (ACI 544.5R). Fibers inhibit further crack propagation by providing bridging forces across the crack surfaces (Grzybowski and Shah 1990; Kim et al. 2008). Numerous studies have been conducted on the effects of fibers on fresh concrete and plastic shrinkage cracking behavior, as summarized in the following paragraphs. These studies generally state that while fiber addition does not influence the evaporation rate, proportioning concrete mixtures with around 0.1 to 0.2 percent volume fraction of very fine fibers eliminate or significantly reduce plastic shrinkage cracks in concrete exposed to hot weather condition.

Various types of fibers such as alkali-resistant (AR) glass, polypropylene, carbon, polyvinyl alcohol, and steel have been studied by various authors, as they influence the cumulative moisture loss and evaporation rate of freshly mixed concrete, cement paste, or both (Bakhshi and Mobasher 2011; Naaman et al. 2005; Wongtanakitcharoen and Naaman 2007). Results of these studies conclude that fiber addition has no significant effect on reducing the cumulative moisture loss (within 5 percent or less), and only a slight reduction in evaporation rates at the early stage of drying by less than 10 percent was observed.

The plastic shrinkage cracking characteristics of concrete containing different types of fibers was studied by Wongtanakitcharoen and Naaman (2007) and Naaman et al. (2005). The two most influential parameters in controlling plastic shrinkage cracking were the fiber volume fraction and diameter. At a fiber volume fraction of 0.2 percent, plastic shrinkage cracking was reduced to approximately 10 percent of the plain concrete.

Concrete with steel, glass, and polypropylene fibers at volume fraction of 0.1 percent were also tested under restrained plastic shrinkage cracking using an experimental setup similar to ASTM C1579-13 (Rahmani et al. 2012). Results of maximum crack width and total crack area showed a reduction by as much as 30 to 50 percent and 40 to 60 percent, respectively, while the formation of first crack was delayed.

Low-pressure drying test methods were also used to study the effect low dosage rates of AR glass fibers on shrinkage cracking of fresh cement paste (Bakhshi and Mobasher 2011). Fractional areas of cracks were reduced by 20 and 60 percent, respectively, using 0.1 and 0.2 percent volumetric fractions of glass fibers. In addition, maximum crack width was significantly reduced (approximately 50 to 70 percent) in comparison to control samples.

Plastic shrinkage cracking in polyolefin fiber-reinforced concrete (FRC) using a substrate restraint type shrinkage test was studied by Banthia et al. (1996) and Banthia and Yan (2000). Results include a crack width reduction from 0.005 in. (1 mm) in plain concrete to less than 0.002 in. (0.40 mm) with 0.7 percent volumetric fraction of 2 in. (50 mm) long fibers. Cracks were eliminated in concrete with reduced fiber length at similar aspect ratio and volume fractions.

Effect of polypropylene fibers at volumetric dosage varying from 0.1 to 0.3 percent in fully bonded overlays was investigated by Banthia and Gupta (2006). It was concluded that, in general, polypropylene fibers were effective in controlling plastic shrinkage cracking in concrete and found finer fibers to be more effective than coarser fibers, whereas longer fibers are more effective than shorter ones. Furthermore, fiber fibrillations appear to be highly effective in controlling plastic shrinkage cracking. A volumetric fraction of 0.2

percent fibrillated and finer monofilament polypropylene fibers result in reduction of total crack area and maximum crack width by more than 85 percent. This is in agreement with other studies that used image analysis to systematically characterize the size of the plastic shrinkage cracks (Qi et al. 2003). It is expected that coarse monofilament fibers only reduce the width of the cracks and do not eliminate the cracks. For the case of reinforcement with fine fibrillated polypropylene fiber, image analysis results prove that crack elimination is possible once the fiber content reaches a critical volume of 0.1 percent. Using 0.4 percent volume fiber, it is expected that 50 percent of the concrete surface remain uncracked when fresh concrete is exposed to a restrained shrinkage test setup similar to ASTM C1579-13 under a constant temperature of 100°F (38°C), relative humidity of 50 percent, and wind velocity of 15 mph (24 km/h).

Numerical and empirical models addressing the shrinkage cracking behavior of joint-free steel fiber-reinforced concrete (SFRC) slabs were studied by Destree et al. (2016). Effect of water-cement ratio (*w/c*), admixtures, and free shrinkage were used in the model. Mechanical restrictions, including base friction, fiber dosage, and interfacial bond properties, restrain the growth of microcracks into main cracks and reduce crack opening. A model based on a finite-difference equilibrium solution of a one-dimensional slab on frictional ground simulates the formation and subsequent opening of cracks in the slab. Results were compared with an empirical predictive tool for crack opening. A sensitivity study shows that correlation of predicted crack opening reduced by increasing fiber volume, base friction, and interfacial bond strength.

## 4.11—Proportioning

Mixture proportions should be established or adjusted based on field performance records in accordance with ACI 318, provided that the records indicate the effect of expected seasonal temperatures and delivery times.

The selection of ingredients and their proportions should be guided by their contribution to satisfactory performance of the concrete under hot weather conditions (ACI 211.1; ACI 211.2). The cement content should be kept as low as possible, but sufficient to meet strength and durability requirements. Inclusion of supplementary cementitious materials, such as fly ash or slag cement, should be considered to delay setting and to mitigate the temperature rise from heat of hydration. The use of various types of water-reducing admixtures can offset increased water demand and strength loss that could otherwise be caused by higher concrete temperatures. High-range water-reducing retarders formulated for extended slump retention should be considered where longer delivery periods are anticipated. Unless required otherwise, concrete should be proportioned for a slump necessary to permit prompt placement and effective consolidation in the form.

**4.11.1** *Trial batches*—The performance of the concrete mixtures should be verified under conditions approximating the delivery time and hot weather environment expected at the project. Trial batches used to select proportions are normally prepared in accordance with ASTM C192/C192M. The method requires concrete materials to be at room temperature (in the range of 68 to 86°F [20 to 30°C]). Trial batches, however, should also be performed at the expected maximum placing temperature using a mixing and agitating period longer than that required in ASTM C192/C192M to help define the performance to be expected. This may require preconditioning of concrete materials to a higher temperature prior to batching, or performing job-site trials including verification of slump loss, or both.

When determining mixture proportions using trial batches, estimate the slump loss during the period between first mixing of the concrete and its placement in the form by use of Procedure A, B, or C below.

**4.11.1.1** *Procedure A: Laboratory trial batches*

1. Prepare the batch using ASTM C192/C192M procedures but add 10 percent additional water over that normally required
2. Mix initially in accordance with ASTM C192/C192M (3 minutes of mixing followed by a 3-minute rest and a 2-minute remixing)
3. Determine the slump and record as initial slump
4. Continue mixing for 15 minutes
5. Determine the slump and record as estimated placement slump. Experience has shown this slump correlates with that expected for 30- to 40-minute delivery time. If this slump does not meet the specification limits, either discard and repeat the procedure with an appropriate water adjustment or add water to give the required slump and then test the concrete
6. Determine other properties of fresh concrete (temperature, air content, unit weight), and mold strength test specimens

**4.11.1.2** *Procedure B: Laboratory trial batches*

1. Prepare the batch using ASTM C192/C192M procedures for the specified slump
2. Mix in accordance with ASTM C192/C192M (3 minutes of mixing followed by a 3-minute rest and a 2-minute remixing) and confirm the slump
3. Stop the mixer and cover the batch with wet burlap
4. After 20 minutes, remix for 2 minutes, adding water to produce the specified slump. The total water (initial water plus the remixing water) can be expected to equal that required at the batch plant to give the required job site slump
5. Determine other properties of fresh concrete (temperature, air content, and unit weight) and mold-strength test specimens

**4.11.1.3** *Procedure C: Trial batches*

The use of full-size production batches may be considered for verification of mixture proportions as an alternative to Procedures A or B, provided the expected maximum temperature of the concrete can be attained. This may be the preferred method when admixtures selected for extended slump retention are used. Careful recording of batch quantities at the plant and of water added for slump adjustment before sampling is required. Sampling procedures of ASTM C172/C172M should be strictly observed. Verification of

slump loss can be performed by taking slump measurements every 20 minutes for at least 2 hours after batching.

## CHAPTER 5—PRODUCTION AND DELIVERY

### 5.1—General

Production facilities and procedures should be capable of providing the required quality and quantity of concrete under hot weather conditions at production rates required by the project. Satisfactory control of production and delivery operations should be assured. Concrete plant and delivery units should be inspected and in good operating condition. Intermittent stoppage of deliveries due to equipment breakdown can be much more serious under hot weather conditions than in moderate weather. Because of this, a contingency plan should be established during the preplacement meeting to assure uninterrupted supply of concrete.

In hot weather concreting operations, concrete placements can be scheduled at times other than during daylight hours, such as during the coolest part of the morning. Night-time production requires additional planning and lighting.

### 5.2—Temperature control of concrete

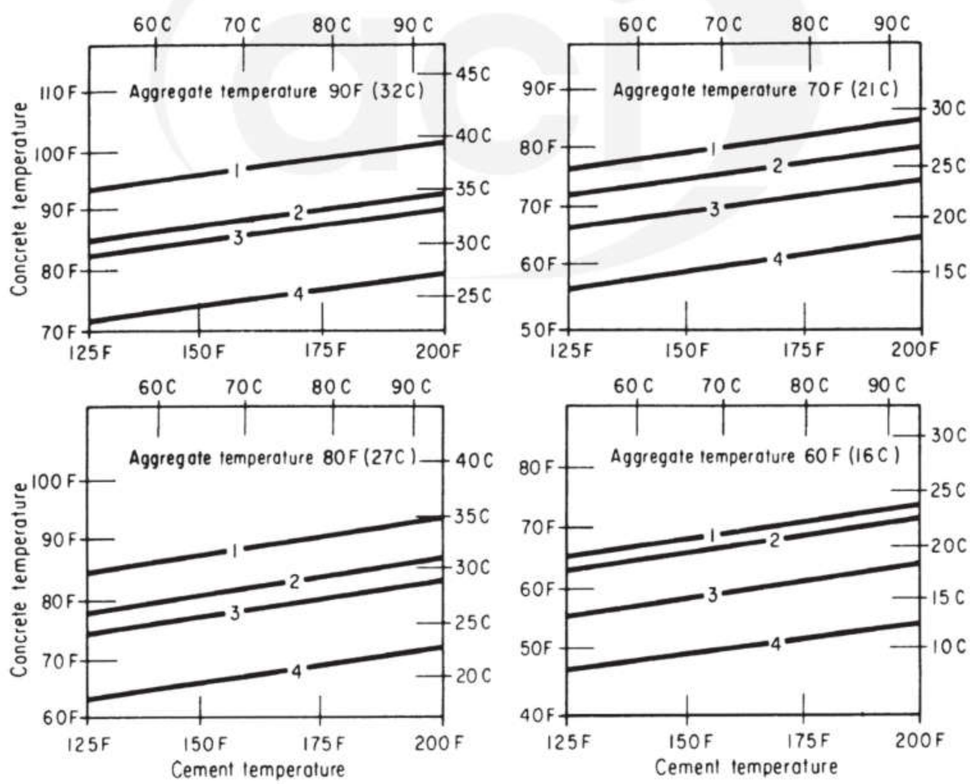
When proper planning and precautions are taken in all aspects of concrete production from proportioning to curing, concrete of acceptable quality can be produced at a predetermined maximum placement temperature established for specific site conditions. Throughout planning, production, and delivery, every effort should be made to keep the temperature of the fresh concrete as low as practical. Using the relationships given in Appendix A, it is shown, for example, that the temperature of concrete is reduced by 1°F (0.5°C) if any of the following reductions are made in material temperatures:

a) 8°F (4.4°C) reduction in cement temperature

b) 5°F (2.7°C) reduction in water temperature

c) 1.5°F (0.8°C) reduction in the temperature of the aggregates

**5.2.1** *Aggregate cooling*—Figure 5.2.1 shows the influence of the temperature of concrete ingredients on concrete temperature. As the greatest portion of concrete is aggregate, reduction of aggregate temperature brings about the greatest reduction in concrete temperature. Therefore, all practical means should be employed to keep the aggregates as cool as possible. Shaded storage of fine and coarse aggregates will lower the temperature of the aggregates. Sprinkling coarse aggregates with cool water reduces aggregate temperature by evaporation and direct cooling (Lee 1987). Passing water through a properly sized evaporative cooling tower will chill the water to the wet bulb temperature. This procedure




Curve (1) - Mixing water at temperature of aggregate

Curve (2) - Mixing water at 50 F (10 C)

Curve (3) - Mixing water at temperature of aggregate; 25 percent of mixing water by weight replaced by ice

Curve (4) - Mixing water at temperature of aggregate; 50 percent of mixing water by weight replaced by ice

*Fig. 5.2.1—Influence of temperature of concrete ingredients on concrete temperature (calculated from equations in Appendix A).*

has greater effects in areas that have low relative humidity. Wetting of aggregates can cause variations in surface moisture. Moisture tests or the use of moisture probes are necessary to ensure that the correct batch adjustments are made. Above-ground storage tanks for mixing water should be provided with shade and thermal insulation. Silos and bins absorb less heat if coated with heat-reflective paints.

**5.2.2** *Mixer drum color*—Painting mixer surfaces white to minimize solar heat gain also helps. Based on a 1-hour delivery time on a hot, sunny day, concrete in a clean, white mixer drum, should be 2 to 3°F (1 to 1.5°C) cooler than in a black or red mixer drum, and 0.5°F (0.3°C) cooler than in a cream-colored drum. When an empty mixer drum stands in the sun for an extended period before concrete is batched, the heat stored in the white mixer drum will raise concrete temperatures 0.5 to 1°F (0.3 to 0.5°C) less than a yellow or red mixer drum. Spraying the exterior of the mixer drum with water before batching or during delivery has been suggested as a means of minimizing concrete temperature, but it provides only a marginal benefit.

**5.2.3** *Project plan*—Setting up the means for cooling sizeable amounts of concrete production requires planning well in advance of placement and installation of specialized equipment. This can include chilling of batch water by water chillers or heat pump technology as well as other methods, such as substituting crushed or flaked ice for part of the mixing water, or cooling by liquid nitrogen. Delivery of the required quantity of cooling materials should be ensured for each placement.

Details for estimating concrete temperatures are provided in Appendix A. Various cooling methods are described in Appendix B. The general influence of the temperature of concrete ingredients on concrete temperature is calculated from the equations in Appendix A and shown in Fig. 5.2.1.

## 5.3—Batching and mixing

Batching and mixing are described in ACI 304R. Procedures under hot weather conditions are not different from good practices under normal weather conditions. Producing concrete with specified properties, such as slump, is essential because an interruption in the concrete placement due to rejection can cause the formation of cold joints or serious finishing problems. Testing of concrete is discussed in Chapter 7.

For truck-mixed concrete, an initial mixing of approximately 70 revolutions at the batch plant before transporting allows for an accurate verification of the condition of the concrete, primarily its slump and air content. Generally, centrally mixed concrete can be inspected visually as it is being discharged into the transportation unit.

**5.3.1** *Slump control*—Slump can easily change due to minor changes in materials and concrete characteristics. For example, an undetected change of only 1.0 percent moisture content of the fine and coarse aggregates could change slump by 1 to 2 in. (25 to 50 mm) (ACI 211.1). An error range of approximately 0.5 percent in the determination of aggregate moisture complicates moisture control, even with advanced systems. To avoid producing slump higher than specified, plant operators often batch concrete to a lower slump. Care should be taken to avoid withholding excessive water from the batch, as this could result in inadequate mixing, dry-packing, reduction in the effectiveness of chemical admixtures, or delivery at a slump below the specified minimum. Reduced workability may increase interparticle friction in transit that can lead to a slight increase in concrete placing temperature at point of delivery.

**5.3.2** *Hydration control*—Hot weather conditions and extended hauling time can indicate a need to split the batching process by batching the cement at the job site, or layering the materials in the mixer drum at the plant to keep some of the cement dry and then mixing the concrete after arrival at the job site. This, however, can decrease concrete uniformity between loads. These methods can, on occasion, offer the best solution under existing conditions. A better-controlled concrete can usually be provided when all materials are batched at the concrete production facility.

By using set-retarding or extended set-control admixtures at appropriate dosages, preferably in combination with supplementary cementitious materials, concrete can be maintained in a workable condition for extended periods, even in hot weather (4.8). Field experience indicates that concrete set retardation can be extended further by separately batching the retarding admixture with a small portion of mixing water (1 to 2 gal./yd$^3$ [5 to 10 L/m$^3$]), after the concrete has been mixed for several minutes. Extended set-control admixtures offer more predictable setting times than set-retarding admixtures and may offer a better solution during hot weather conditions, especially on projects that require extended slump life. The use of set-retarding or extended set-control admixtures, together with the cementitious materials and other ingredients proposed for the project, should be evaluated in the field for desired properties. Should the slump be lower than required, the use of mid-range or high-range water-reducing admixtures is recommended to increase the concrete slump. Workability-retaining admixtures may also be used to extend slump life without extending the set time of the concrete.

**5.3.3** *Mixer control*—Under hot weather conditions, mixer revolutions at mixing speed should be held to a minimum to avoid unnecessary heat gain of the concrete (ACI 207.4R). For efficient mixing, mixers should be free of buildup of hardened concrete and excessive wear of mixer blades. As soon as the concrete has been mixed to a homogeneous condition, all further drum rotation should be at the lowest agitating speed of the unit (generally one revolution per minute). The drum should not be stopped for extended periods of time because there is the potential for false setting problems to cause the concrete to stiffen rapidly or set in the drum, or to flatten the mixer rollers.

Specifications that govern the number of truck mixer drum revolutions or time to discharge may be waived in accordance with ASTM C94/C94M for:

a) Concrete that retains its workability without the addition of water

b) Separate addition of high-range water-reducing admixtures

c) Direct addition of liquid injected nitrogen into the mixer as a means of lowering the concrete temperature

## 5.4—Delivery

While the concrete is in the mixer, cement hydration, temperature rise, slump loss, aggregate grinding, and change of air content all occur with the passage of time; thus, the period between start of mixing to placement of the concrete should be minimized. Coordination of mixer truck dispatching with the rate of concrete placement helps to avoid delays in arrival or waiting periods until discharge. On major concrete placements, provisions should be made for good communication between the job site and concrete production facility, and they should be scheduled during periods of lower urban traffic. If slow placement is anticipated or observed, consideration should be given to one or more of the following: reducing load size, the use of set retarding or extended set-control admixtures, or the use of cooled concrete.

## 5.5—Slump adjustment

Fresh concrete is subject to slump loss with time, whether it is used in moderate or hot weather. Slump changes between plant and job site should be established for given materials and mixture proportions. If, on arrival at the job site, the slump is less than the specified maximum, additional water can be added if the maximum allowable water content is not exceeded, in accordance with ASTM C94/C94M. Slump increases should be allowed when chemical admixtures are used, provided that the admixture-treated concrete has the same or lower *w/cm* and does not exhibit segregation potential.

## 5.6—Properties of concrete mixtures

The proposed mixtures should be suitable for expected job conditions. This is particularly important when there are no limits on ambient placing temperatures, as is the case in most construction in warmer regions. Use of cements or cementitious materials that perform well under hot weather conditions, in combination with water-reducing and set-retarding or extended set-control admixtures, can provide concrete with the required properties (Mittelacher 1985). When using high-range water-reducing and retarding admixtures, products should be selected that provide extended slump retention in hot weather (Collepardi et al. 1979; Guennewig 1988). In dry and windy conditions, the setting rate of concrete used in flatwork should be adjusted to minimize plastic shrinkage cracking or crusting of the surface, whereas the lower layer remains in a plastic condition. The type of adjustment depends on local climatic conditions, timing of placements, and concrete temperatures. A change in quantity or type of admixture or cementitious materials can often provide the desired setting time.

## 5.7—Retempering

Laboratory research, as well as field experience, shows that strength reduction and other detrimental effects are proportional to the amount of retempering water added. Therefore, water additions exceeding the proportioned maximum water content or *w/cm* to compensate for loss of workability should be prohibited. Adding chemical admixtures, particularly high-range water-reducing admixtures, can be very effective to maintain workability. These additions can be made at the plant, in transit, and at the job site.

# CHAPTER 6—PLACING AND CURING

## 6.1—General

**6.1.1** Properly placing concrete in hot weather requires the minimum following steps:

a) The concrete mixture should be designed to accommodate hot weather concreting

b) A pre-concrete-placement meeting should be held to discuss aspects of hot weather concreting

c) Concrete should be transported and placed where it is to remain, with minimum segregation and slump loss

d) Concrete should be placed in layers shallow enough to assure proper consolidation into the layer below, and that the elapsed time between layers should be minimized to avoid cold joints

e) Timing of finishing operations should be guided only by the readiness of the concrete

f) Curing and protection should be conducted so that at no time during placing, finishing, and curing operations will the concrete lack ample moisture and temperature control to develop its full potential strength and durability

g) Construction joints should be made on sound, clean concrete (refer to ACI 224.3R)

**6.1.2** Details of placing, consolidating, and curing concrete are described in ACI 304R, 309R, and 308R, respectively. This chapter includes information on how hot weather can affect those operations, as well as the resulting concrete. Also included are recommendations on how to prevent or offset the influence of hot weather.

## 6.2—Preparations for placing and curing

**6.2.1** *Planning hot weather placements*—At least 30 days prior to the start of hot weather concrete construction, a pre-concrete-placement meeting should be held to review the proposed concrete mixtures and to discuss the required methods and procedures to achieve the requirements of the project. A pre-concrete-placement meeting agenda should be sent to all attendees prior to the scheduled date of the meeting. The meeting discussion should include plans to minimize the exposure of concrete to adverse hot weather conditions. Whenever possible, minimize effect of drying winds by erecting wind breaks or by placing the slab on ground after the walls and roof structure are in place. A roof also reduces thermal shock from rapid temperature changes, or by cool rain on concrete heated by the sun. Under hot weather conditions, scheduling concrete placements during early morning or late-night hours may be advisable. Considerations include ease of handling and placing as well as minimizing the risk of plastic shrinkage and thermal cracking.

**6.2.2** *Preparing for ambient conditions*—Personnel in charge of concrete construction during hot weather condi-

tions should be aware of damaging combinations of high air temperature, direct sunlight, drying winds, and high concrete temperature. Local weather reports should be monitored, and routine recordings of site conditions should be made, including air temperature, sun exposure, relative humidity, and prevailing winds. These data, together with projected or actual concrete temperatures, enable supervisory personnel, using Fig. 4.1.1b, to determine and prepare required protective measures. Equipment should also be available at the site to measure evaporation rate (refer to 4.2).

**6.2.3** *Expediting placement*—Preparations should be made to transport, place, consolidate, and finish concrete as expeditiously as possible. Concrete placements can be affected when concrete is delivered prematurely, resulting in loss of slump and workability at the most critical time. Concrete delivery to the site should be scheduled so that concrete is placed promptly on arrival, particularly the first batch. Stable roadways at the site ensure easy access of delivery units to the unloading points, minimizing delays. Site traffic should be also coordinated for a quick turnaround. If possible, large or critical placements should be scheduled during periods of low traffic loads.

**6.2.4** *Placing equipment*—Equipment for placing concrete should be of suitable design and have ample capacity to perform efficiently. All equipment should have adequate power for the work and be in excellent operating condition. Breakdowns or delays that stop or slow placements can seriously affect the quality and appearance of the work. Arrangements should be made for readily available backup equipment. Concrete pumping equipment should be capable of pumping the specified class of concrete through the length of line and elevation at required rates per hour. Where placement is by crane and buckets, wide-mouth buckets with steep-angled walls should be used to permit rapid and complete discharge of bucket contents. Adequate means of communication between bucket handlers and placing crew should be provided to ensure that concrete is charged into buckets only when the placing crew is ready to use the concrete without delay. Concrete should not be allowed to rest exposed to the sun and high temperature before it is placed into the form. To minimize concrete heat gain during placement, delivery units, conveyors, pumps, and pump lines should be kept shaded when possible. In addition, pump lines should be painted white and cooled. Pump lines can also be cooled by covering or wetting with a soaker hose or other cooling methods proven effective.

**6.2.5** *Consolidation equipment*—Poorly consolidated concrete can seriously impair the appearance, durability, and structural performance of reinforced concrete. Therefore, ample workers and vibration equipment should be available to properly consolidate concrete immediately as it is placed into forms. Procedures and equipment are described in ACI 309R. Standby vibrators should also be available, including at least one standby for every three vibrators in use. If the site is subject to occasional power outages, portable generators should also be available for uninterrupted vibrator operation.

**6.2.6** *Preparations for protecting and curing the concrete*—Prior to concrete placement, a sufficient supply of water should be available at the project site for moistening the subgrade, as well as for fogging forms and reinforcement. For moist curing, care needs to be taken to avoid thermal shock or excessively steep thermal gradients due to the use of cold or hot curing water. Fog nozzles should produce a fog blanket. They should not be confused with common garden-hose nozzles, which generate an excessive washing spray. Pressure washers with a suitable nozzle attachment can be a practical means for fogging on smaller sites. Materials and means should be on hand for erecting temporary windbreaks and shades as needed to protect against drying winds and direct sunlight. Plastic sheeting or sprayable moisture-retaining (monomolecular) films, also referred to as evaporation reducers, should be available to reduce evaporation from flatwork between finishing passes. If concrete is placed during hot weather conditions and exposed to rapid temperature drops, thermal protection should be provided to protect against thermal shrinkage cracking. Finally, curing materials should be readily available at the project site to permit prompt protection of all exposed concrete surfaces from premature drying upon completion of the placement.

**6.2.7** *Planning incidental work*—Hot weather concreting can accelerate the initial and final set times of concrete. Timing of final operations, including curing, saw-cutting, and slab measurements, should be expedited as quickly as possible. These operations should be planned in advance, including the timely sawing of contraction joints in flatwork to minimize cracking due to excessive tensile stress. Typically, joints that are cut using a conventional wet or dry process are made within 4 to 12 hours after the slab has been finished—4 hours in hot weather, and up to 12 hours in cold weather. For early entry dry-cut saws, the waiting period will typically vary from 1 hour in hot weather to 4 hours in cold weather (ACI 302.1R). Slab-on-ground tolerance measurements should be taken in accordance with ASTM E1155.

## 6.3—Placement and finishing

**6.3.1** *General*—When the concrete placing rate is not coordinated with the available work force and equipment, the quality of work will be marred by poor consolidation, cold joints, and inadequate surface finishes. Delays invite the addition of water to offset loss in slump and workability. Well-coordinated, expeditious placement and finishing reduces hot weather difficulties. Each operation in finishing should be carried out as soon as the concrete is ready; however, concrete should not be placed faster than it can be properly consolidated and finished.

**6.3.2** *Placing formed concrete*—During hot weather conditions, concrete should be placed in shallow layers to ensure proper consolidation of the lower layer. The interval between monolithic wall and deck placements becomes very short in hot weather. This interval can be extended by the judicious use of set-retarding admixtures.

**6.3.3** *Placement of flatwork*—When concrete is deposited for slabs-on-ground, the subgrade should be moist, but free of standing water and soft spots. During hot weather, it may be necessary to keep the operation confined to a small area and to proceed with a minimum amount of exposed surface

to which concrete is added. A fog nozzle should be used to cool the air, to cool any forms and steel immediately ahead, and to lessen rapid evaporation from the concrete surface before and after each finishing operation. Excessive fog application (which would wash the fresh concrete surface or cause surplus water to cling to reinforcement or stand on the concrete surface during floating and troweling) should be avoided. Other means of reducing moisture loss include spreading and removing impervious sheeting or applying sprayable moisture-retaining (monomolecular) films one or more times as needed between finishing operations. Finishing of slabs on ground should begin after the surface sheen of the (monomolecular) film has disappeared. These products should not be used as finishing aids or worked into the surface, as concrete durability can be reduced. The product manufacturer should be contacted for information on proper application rates. These procedures can cause a slight in-place increase in concrete temperature due to reduced evaporative cooling. Generally, the benefit from reduced moisture evaporation is more important than the increase of in-place concrete temperature (Berhane 1984).

**6.3.4** *Plastic shrinkage cracks*—Without protection against moisture loss, plastic shrinkage cracks can occur (refer to 4.1.4). Merely troweling slurry over the cracks will not be effective because these are likely to reappear if the surface is not properly protected to avoid evaporation. In large placements, additional vibration just prior to floating can sometimes close this type of cracking. Before the concrete reaches final set, plastic shrinkage cracks can frequently be closed by striking the surface on each side of the crack with a float. The affected area is then retroweled to a level finish.

## 6.4—Curing and protection

**6.4.1** *General*—Immediately following completion of finishing operations, efforts should be made to protect the concrete from low humidity, drying winds, and extreme ambient temperature differential. Whenever possible, the concrete and surrounding formwork should be kept in a uniform moisture and temperature condition to allow the concrete to develop its maximum potential strength and durability. High initial curing temperatures can negatively affect ultimate strength and durability to a greater degree than high placement temperatures of fresh concrete (Bloem 1954; Barnes et al. 1977; Gaynor et al. 1985). Procedures for keeping exposed surfaces from drying should begin promptly and continue without interruption. Failure to do so can result in excessive drying shrinkage and related cracking, which can impair the surface durability of concrete. Approved curing methods should be continued for at least 7 days. Concrete surfaces should not be allowed to become surface-dry at any point during the transition. A variety of curing methods are described in ACI 308R, including the concept of initial curing during the plastic stage of the concrete. Initial curing techniques, such as fog spray, can be used to ensure timely replacement of bleed water and avoidance of plastic shrinkage cracking. Concrete should also be protected against thermal shrinkage cracking due to rapid temperature drops, particularly during the first 24 hours. Thermal shrinkage cracking from a rapid temperature drop is associated with a cooling rate of more than 5°F (3°C) per hour, or more than 50°F (28°C) in a 24-hour period for concrete with a least dimension less than 12 in. (300 mm). Concrete exposed to rapid cooling at an early age develops lower tensile strain capacity and is more susceptible to other types of shrinkage cracking than concrete that cools at a slower rate (ACI 207.4R). Hot weather patterns increase the potential for thermal cracking due to vast day and night temperature differences. Additionally, seasonal weather patterns often include passing cold fronts that produce rain, which can induce thermal shock to exposed concrete sections. Under these conditions, concrete should be protected by placing waterproof material over the exposed concrete, or by using other insulating methods and materials described in ACI 306R.



**6.4.2** *Moist curing of flatwork*—When maintained properly, moist curing is usually the best method for maximizing strength and durability, as well as minimizing early-age drying shrinkage of concrete slabs-on-ground. Moist curing is especially beneficial for mixtures with high replacement levels of supplementary cementitious materials (SCMs). Moist curing methods include ponding, covering exposed concrete surfaces with clean sand kept continuously wet, fog-spraying, or continuous sprinkling. These methods require a sufficient water supply and disposal of any runoff. Where sprinkling is used, care should be taken that surface erosion does not occur. A common and practical method of moist curing is to cover the concrete with impervious sheeting or fabric mats kept continuously wet with a soaker hose or similar means. Other suitable coverings are described in ACI 308R. Curing materials should be rolled out flat, staying in contact with the concrete surface at all times. Alternating cycles of wetting and drying should be avoided, as it will result in pattern cracking. The temperature of water used for initial curing should be as close as possible to that of the concrete to avoid thermal shock.

**6.4.3** *Membrane curing of flatwork*—When site conditions are not favorable for moist curing, the most practical method for curing concrete is the use of a liquid membrane-forming compound. The membrane restricts the loss of moisture from the concrete, thereby allowing the development of strength, durability, and abrasion resistance of the surface. When applicable, concrete surfaces exposed to direct sunlight can use heat-reflecting, white-pigmented compounds to increase albedo (reflectivity). Compounds containing non-yellowing ultraviolet blockers may also be considered for outdoor work. Note that the solids and moisture-retention rates vary considerably between products. For use in hot weather conditions, a material should be selected that ensures equal or greater moisture retention than required by ASTM C1315, limiting the moisture loss in a 72-hour period in excess of 6.6 lb/yd$^3$ (4.0 kg/m$^3$) when tested per ASTM C156. Application of a liquid membrane-forming compound should immediately follow the disappearance of surface water sheen after the final finishing pass. During application, the compound should be applied in an even, continuous film, using a spray nozzle that is positioned suffi-

ciently close to the surface to ensure the specified application rate and prevent wind-blown dispersion. Dissipating or removable curing compounds may be applied to surfaces on which additional concrete or other bonded materials will be placed, provided the curing compound is removed such that bond is not adversely affected.

**6.4.4** *Concrete in formwork*—Forms should be covered and kept continuously moist during the early curing period. Formwork should be loosened or removed at the earliest practical age without damage to the concrete, and provisions should be made for an approved curing method to begin. Following formwork removal, tie holes and significant defects can be filled and repairs made by exposing the smallest practical section of concrete at one time to perform the work. All repairs should be completed within the first few days following form stripping, allowing the repaired areas to cure with the surrounding concrete. At the end of the curing period, the covering should be left in place without wetting for several days (4 days is suggested) so that the concrete surface will dry slowly and be less prone to surface shrinkage cracking. Surface cracking due to drying can be minimized by applying a liquid membrane-forming curing compound to exposed surfaces at the end of the moist-curing period.

# CHAPTER 7—TESTING AND INSPECTION

## 7.1—Testing

Tests on the fresh concrete sample should be conducted and specimens prepared in accordance with ASTM C31/C31M, C138/C138M, C143/C143M, C172/C172M, C231/C231M, C232/C232M, C173/C173M, C1064/C1064M, C1611/C1611M, and C1621/C1621M, as appropriate. Tests should be performed by a certified ACI Concrete Field Testing Technician – Grade I. ASTM C31/C31M requires that the concrete samples be protected from exposure to sun, wind, rapid evaporation, and contamination. Failure to do so will not provide valid test results. High temperature, low relative humidity, and drying winds affect the rate of evaporation of the concrete sample surface when not protected properly as recommended by ASTM C31/C31M.

It is desirable in hot weather to conduct tests, such as slump, air content, ambient and concrete temperature, relative humidity, and density (unit weight), more frequently than in normal conditions.

**7.1.1** *Curing test specimens*—Particular attention should be given to the protection and curing of strength test specimens used as a basis for acceptance of concrete. Due to their small size, test specimens are quickly influenced by changes in ambient temperatures. Extra care is needed in hot weather to maintain strength test specimens at a temperature of 60 to 80°F (16 to 27°C) for less than 6000 psi (40 MPa), and 68 to 78°F (20 to 26°C) for greater than or equal to 6000 psi (40 MPa). Care is also needed to prevent moisture loss during the initial curing period, in accordance with ASTM C31/C31M, with the exception of C1611/C1611M and C1621/C1621M for self-consolidated concrete. The specimens should be provided with an impervious cover and placed in a temperature-controlled cylinder box immediately after molding. When stored outside, exposure to the sun should be avoided. Curing in a no-moisture-loss environment within the prescribed temperature range is also required.



Molds should not be manufactured of a material that expands when in contact with moisture or when immersed in water, and should meet the requirements of ASTM C470/C470M. Merely covering the top of the molded test cylinder with a lid or plate is usually not sufficient in hot weather to prevent loss of moisture and to maintain the required initial curing temperature. During the transfer to the testing facility, the specimens should be kept moist and be protected and handled carefully. They should then be stored in a moist condition at 73 ± 3.5°F (23 ± 2.0°C) until the moment of testing as per ASTM C31/C31M.

**7.1.2** *Additional test specimens*—Specimens, in addition to those required for acceptance, can be made and cured at the site to assist in determining when formwork can be removed, when shoring can be removed, and when the structure can be placed in service. Unless the temperature and moisture conditions of concrete specimens used for these purposes match those of the concrete in the structure they are to represent, results of the tests can be misleading. Alternative test methods for determining in-place concrete strength are described in ASTM C900, C1074, and C918/C918M.

## 7.2—Inspection

**7.2.1** The numerous details to be considered in concrete construction are covered in ACI MNL-2 and ACI 311.4R. Project inspection of concrete is necessary to ensure and document compliance with previously mentioned precautions and procedures. The need for such measures, such as spraying of forms and subgrade, cooling concrete, providing sunshades and windscreens, the use of evaporation retarders or fogging, and minimizing delays in placement, initial curing, and final curing procedures, should be observed and documented when the rate of evaporation is higher than the rate of bleed water coming to the surface.

**7.2.2** Air temperature, concrete temperature (ASTM C1064/C1064M), general weather conditions (clear or cloudy), wind speed, relative humidity, and evaporation rate should be recorded at hourly intervals. The measurements should be taken per the instructions in Fig. 4.1.1b. In addition, the following should be recorded and identified with the work in progress so that conditions relating to any part of the concrete construction can be identified at a later date:

a) All water added to the concrete with corresponding mixing times

b) Time batched, time discharge started, and time discharge completed

c) Concrete temperature at time of delivery and after concrete is placed

d) Observations on the appearance of concrete as delivered and after placing in forms

e) Slump of concrete at point of delivery

f) Protection methods

g) Initial curing method used

h) Final curing method used

i) When a liquid membrane-forming curing compound is used, the time and rate of application and visual appearance of concrete

j) Duration and termination of curing

These observations should be included in the permanent project records.

## CHAPTER 8—REFERENCES

### 8.1—Referenced standards and reports

Committee documents are listed first by document number and year of publication followed by authored documents listed alphabetically.

*American Concrete Institute*

ACI 201.2R-16—Guide to Durable Concrete

ACI 207.1R-05(12)—Guide to Mass Concrete

ACI 207.2R-07—Report on Thermal and Volume Change Effects on Cracking of Mass Concrete

ACI 207.4R-05(12)—Cooling and Insulating Systems for Mass Concrete

ACI 211.1-91(09)—Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete

ACI 211.2-98(04)—Standard Practice for Selecting Proportions for Structural Lightweight Concrete

ACI 212.3R-16—Report on Chemical Admixtures for Concrete

ACI 221R-96(01)—Guide for Use of Normal Weight and Heavyweight Aggregates in Concrete

ACI 223R-10—Guide for the Use of Shrinkage-Compensating Concrete

ACI 224.1R-01(08)—Control of Cracking in Concrete Structures

ACI 224.3R-95(13)—Joints in Concrete Construction

ACI 225R-19—Guide to the Selection and Use of Hydraulic Cements

ACI 232.2R-18—Report on the Use of Fly Ash in Concrete

ACI 234R-06(12)—Guide for the Use of Silica Fume in Concrete

ACI 301-16—Specifications for Structural Concrete

ACI 302.1R-15—Guide for Concrete Floor and Slab Construction

ACI 304R-00(09)—Guide for Measuring, Mixing, Transporting, and Placing Concrete

ACI 305.1-14—Specification for Hot Weather Concreting

ACI 306R-16—Cold Weather Concreting

ACI 308R-16—Guide to Curing Concrete

ACI 309R-05—Guide for Consolidation of Concrete

ACI 311.4R-05—Guide for Concrete Inspection

ACI 318-19—Building Code Requirements for Structural Concrete and Commentary

ACI 544.5R-10—Report of Physical Properties and Durability of Fiber Reinforced Concrete

ACI MNL-2(19)—Manual of Concrete Inspection

*ASTM International*

ASTM C31/C31M-19—Standard Practice for Making and Curing Concrete Test Specimens in the Field

ASTM C138/C138M-17a—Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete

ASTM C143/C143M-15a—Standard Test Method for Slump of Hydraulic-Cement Concrete

ASTM C150/C150M-19a—Standard Specification for Portland Cement

ASTM C156-17—Standard Test Method for Water Loss [from a Mortar Specimen] through Liquid Membrane-Forming Curing Compounds for Concrete

ASTM C172/C172M-17—Standard Practice for Sampling Freshly Mixed Concrete

ASTM C173/C173M-16—Standard Test Method for Air Content of Freshly Mixed Concrete by the Volumetric Method

ASTM C192/C192M-18—Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory

ASTM C231/C231M—Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method

ASTM C232/C232M-14(19)—Standard Test Methods for Bleeding of Concrete

ASTM C470/C470M-15—Standard Specification for Molds for Forming Concrete Test Cylinders Vertically

ASTM C494/C494M-17—Standard Specifications for Chemical Admixtures for Concrete

ASTM C595/C595M-19—Standard Specification for Blended Hydraulic Cements

ASTM C618-19—Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete

ASTM C666/C666M-15—Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing

ASTM C900-15—Standard Test Method for Pullout Strength of Hardened Concrete

ASTM C918/C918M-13—Standard Test Method for Measuring Early-Age Compressive Strength and Projecting Later-Age Strength

ASTM C94/C94M-19—Standard Specification for Ready-Mixed Concrete

ASTM C989/C989M-18a—Standard Specification for Slag Cement for Use in Concrete and Mortars

ASTM C1064/C1064M-17—Standard Test Method for Temperature of Freshly Mixed Hydraulic-Cement Concrete

ASTM C1074-19—Standard Practice for Estimating Concrete Strength by the Maturity Method

ASTM C1157/C1157M—Standard Performance Specification for Hydraulic Cement

ASTM C1315-19—Standard Specification for Liquid Membrane-Forming Compounds having Special Properties for Curing and Sealing Concrete

ASTM C1579-13—Standard Test Method for Evaluating Plastic Shrinkage Cracking of Restrained Fiber Reinforced Concrete (Using a Steel Form Insert)

ASTM C1611/C1611M-18—Standard Test Method for Slump Flow of Self-Consolidating Concrete

ASTM C1621/C1621M-17—Standard Test Method for Passing Ability of Self-Consolidating Concrete by J-Ring

ASTM E1115-14—Standard Test Method for Determining FF Floor Flatness and FL Floor Levelness Numbers

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## APPENDIX A—ESTIMATING CONCRETE TEMPERATURE

### A.1—Estimating temperature of freshly mixed concrete

Equations for estimating temperature $T$ of freshly mixed concrete are shown in Eq. (A.1a) through (A.1c).

Without ice (in.-lb and SI units)

$$T = \frac{0.22(T_aW_a + T_cW_c) + T_wW_w + T_aW_{wa}}{0.22(W_a + W_c) + W_w + W_{wa}} \quad \text{(A.1a)}$$

With ice (in.-lb units)

$$T = \frac{0.22(T_aW_a + T_cW_c) + T_wW_w + T_aW_{wa} - 112W_i}{0.22(W_a + W_c) + W_w + W_i + W_{wa}} \quad \text{(A.1b)}$$

With ice (SI units)

$$T = \frac{0.22(T_aW_a + T_cW_c) + T_wW_w + T_aW_{wa} - 79.6W_i}{0.22(W_a + W_c) + W_w + W_i + W_{wa}} \quad \text{(A.1c)}$$

where $T_a$ is temperature of aggregate; $T_c$ is temperature of cement; $T_w$ is temperature of batched mixing water from normal supply excluding ice; $T_i$ is temperature of ice, °F (°C) (Note: Temperature of free and absorbed water on the aggregate is assumed to be the same temperature as the aggregate.); $W_a$ is dry mass of aggregate; $W_c$ is mass of cement; $W_i$ is mass of ice; $W_w$ is mass of batched mixing water; and $W_{wa}$ is mass of free and absorbed moisture in aggregate at $T_a$, lb (kg).

### A.2—Estimating temperature of concrete with ice

Equations (A.1b) and (A.2c), for estimating the temperature of concrete with ice in U.S. customary or SI units, assume that the ice is at its melting point. A more exact approach would be to use Eq. (A.2a) or (A.2b), which includes the temperature of the ice.

With ice (in.-lb units)

$$T = \frac{0.22(T_aW_a + T_cW_c) + T_wW_w + T_aW_{wa}}{0.22(W_a + W_c) + W_w + W_i + W_{wa}} + \frac{T_aW_{wa} - W_i(128 - 0.5T_i)}{0.22(W_a + W_c) + W_w + W_i + W_{wa}} \quad \text{(A.2a)}$$

With ice (SI units)

$$T = \frac{0.22(T_aW_a + T_cW_c) + T_wW_w + T_aW_{wa}}{0.22(W_a + W_c) + W_w + W_i + W_{wa}} + \frac{T_aW_{wa} - W_i(79.6 - 0.5T_i)}{0.22(W_a + W_c) + W_w + W_i + W_{wa}} \quad \text{(A.2b)}$$

## APPENDIX B—METHODS FOR COOLING FRESH CONCRETE

The summary is limited to a description of methods suitable for most structural uses of concrete. Methods for the cooling of mass concrete are explained in ACI 207.4R.

### B.1—Cooling with chilled mixing water

Concrete can be cooled to a moderate extent by using chilled mixing water; the maximum reduction in concrete temperature that can be obtained is approximately 10°F (6°C). The quantity of cooled water cannot exceed the mixing water requirement, which depends on the moisture content of aggregates and mixture proportions. The method involves a significant investment in mechanical refrigeration equipment and insulated water storage large enough for the anticipated hourly and daily production rates of cooled concrete. Available systems include one that is based on heat-pump technology, which is usable for both cooling and heating of concrete. Apart from its initial installation price, this system appears to offer cooling at the lowest price of available systems for cooling mixing water.

### B.2—Liquid nitrogen cooling of mixing water

Mixing water can be chilled rapidly through injection of liquid nitrogen into an insulated holding tank. This chilled water is then dispensed into the batch. Alternatively, the mixing water may be turned into ice slush by liquid nitrogen injection into the mixing water stream as it is discharged into the mixer. The system enables cooling by as much as 20°F (11°C). The ratio of ice to water in the slush should be adjusted to produce the temperature of concrete desired. Installation of this system requires insulated mixing water storage, a nitrogen supply vessel, batch controls, and auxiliary equipment. Apart from the price of installation, there are operating expenses from liquid nitrogen usage and rental fees for the nitrogen supply vessel. The method differs from that by direct liquid nitrogen injection into mixed concrete described in B.4.

### B.3—Cooling concrete with ice

Concrete can be cooled by using ice for part of the mixing water. The amount of cooling is limited by the amount of mixing water available for ice substitution. For most concrete, the maximum temperature reduction is approximately 20°F (11°C). For correct proportioning, the ice should be weighed. Cooling with block ice involves the use of a crusher/slinger unit, which can finely crush a block of ice and blow it into the mixer. A major obstacle to the use of block ice in many areas is insufficient supply. The price of using block ice is: the price of ice, including transportation; refrigerated storage; handling and crushing equipment; additional labor; and, if required, provisions for weighing the ice. An alternative to using block ice is to set up an ice plant near the concrete plant. As the ice is produced, it is weighed, crushed, and conveyed into the mixer. It can also be produced and used as flake ice. This system requires a large capital investment.


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## B.4—Cooling mixed concrete with liquid nitrogen

**B.4.1** Injecting liquid nitrogen into freshly mixed concrete is an effective method for reduction of concrete temperature. The practical lower limit of concrete temperature is reached when concrete nearest the injection nozzle forms into a frozen lump; this is likely to occur when the desired concrete temperature is lower than 50°F (10°C). The method has been successfully used in numerous major concrete placements. The performance of concrete was not affected adversely by its exposure to large amounts of liquid nitrogen. The price of this method is relatively high, but it can be justified on the basis of practical considerations and overall effectiveness.

**B.4.2** Installation of the system consists of a nitrogen supply vessel and injection facility for central mixers, or one or more injection stations for truck mixers. The system can be set up at the construction site for last-minute cooling of the concrete before placement. This reduces temperature gains of cooled concrete in transit between the concrete plant and job site. Coordination is required in the dispatching of liquid nitrogen tanker trucks to injection stations for the timely replenishing of gas consumed in the cooling operations. The quantity of liquid nitrogen required will vary according to mixture proportions and constituents, and the amount of temperature reduction. The use of 135 $ft^3$ (48 $m^3$) of liquid nitrogen will usually reduce concrete temperature 1°F (0.5°C).

## B.5—Cooling of coarse aggregates

**B.5.1** An effective method of lowering the temperature of the coarse aggregate is by cool water spraying or inundation. Coarse aggregate has the greatest mass in a typical concrete mixture. Reducing the temperature of the aggregate approximately 2 ± 1°F (1 ± 0.5°C) lowers the final concrete temperature approximately 1°F (0.5°C). To use this method, the producer should have available large amounts of chilled water and the necessary water-cooling equipment for production requirements. This method is most effective when adequate amounts of coarse material are contained in a silo or bin so that cooling can be accomplished in a short period of time. Care should be taken to evenly inundate the material so that slump variation from load to load is minimized.

**B.5.2** Cooling of coarse aggregate can also be accomplished by blowing air through the moist aggregate. The air flow enhances evaporative cooling and can bring the coarse aggregate temperature within 2°F (1°C) of wet bulb temperature. The effectiveness of the method depends on ambient temperature, relative humidity, and velocity of air flow. The added refinement of using chilled air instead of air at ambient temperature can reduce the coarse aggregate temperature to as low as 45°F (7°C). This method, however, involves a relatively high installation price.


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