

# Hot Weather Concreting

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*Concrete mixed, transported, and placed under conditions of high ambient temperature, low humidity, solar radiation, or wind, requires an understanding of the effects these environmental factors have on concrete properties and construction operations. Measures can be taken to eliminate or minimize undesirable effects of these environmental factors. Experience in hot weather with the types of construction involved will reduce the potential for serious problems.*

*This committee report defines hot weather, lists possible potential problems, and presents practices intended to minimize them. Among these practices are such important measures as selecting materials and proportions, precooling ingredients, special batching, 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 inspecting procedures in hot weather conditions. A selected bibliography is included.*

*These revisions involve an editorial revision of the document. The revisions focus in particular on the effects of hot weather on concrete properties, and the use of midrange water-reducing admixtures and extended set-control admixtures in hot weather.*

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

### CONTENTS

#### Chapter 1—Introduction, p. 305R-2

- 1.1—General
- 1.2—Definition of hot weather
- 1.3—Potential problems in hot weather
- 1.4—Potential problems related to other factors
- 1.5—Practices for hot weather concreting

#### Chapter 2—Effects of hot weather on concrete properties, p. 305R-3

- 2.1—General
- 2.2—Temperature of concrete
- 2.3—Ambient conditions
- 2.4—Water requirements
- 2.5—Effect of cement
- 2.6—Supplementary cementitious materials
- 2.7—Chemical admixtures
- 2.8—Aggregates
- 2.9—Proportioning

#### Chapter 3—Production and delivery, p. 305R-11

- 3.1—General
- 3.2—Temperature control of concrete
- 3.3—Batching and mixing

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- 3.4—Delivery
- 3.5—Slump adjustment
- 3.6—Properties of concrete mixtures
- 3.7—Retempering

#### **Chapter 4—Placing and curing, p. 305R-13**

- 4.1—General
- 4.2—Preparations for placing and curing
- 4.3—Placement and finishing
- 4.4—Curing and protection

#### **Chapter 5—Testing and inspection, p. 305R-16**

- 5.1—Testing
- 5.2—Inspection

#### **Chapter 6—References, p. 305R-17**

- 6.1—Referenced standards and reports
- 6.2—Cited references

#### **Appendix A—Estimating concrete temperature, p. 305R-19**

#### **Appendix B—Methods for cooling fresh concrete, p. 305R-19**

### **CHAPTER 1—INTRODUCTION**

#### **1.1—General**

Hot weather may create problems in mixing, placing, and curing hydraulic cement concrete. These problems 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 is dependent on concrete temperature, cement composition and fineness, and admixtures used.

This report will identify problems created by hot weather concreting and describe practices that will 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. Temperature, volume changes, and cracking problems associated with mass concrete are treated more thoroughly in ACI 207.1R and ACI 224R.

A maximum “as placed” concrete temperature is often used in an effort to control 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 setting a maximum “as placed” or “as delivered” concrete temperature. Concrete durability is a general term that is difficult to quantify, but it is perceived to mean resistance of the concrete to weathering (ACI 201.2R). Generally, if concrete strengths are satisfactory and curing practices are sufficient to avoid undesirable drying of surfaces, durability of hot weather concrete will not differ greatly from similar concrete placed at normal temperatures. The presence of a desirable air-void system is needed if the concrete is going to be exposed to freezing cycles.

If an acceptable record of field tests is not available, concrete proportions may be determined by trial batches (ACI

301 and ACI 211.1). Trial batches should be made at temperatures anticipated in the work and mixed following one of the procedures described in [Section 2.9](#), Proportioning. The concrete supplier and contractor are generally responsible for determining concrete proportions to produce the required quality of concrete unless specified otherwise.

According to ASTM C 31/C 31M, concrete test specimens made in the field that are used for checking adequacy of laboratory mixture proportions for strength or as a basis for acceptance or quality control should be cured initially at 60 to 80 F (16 to 27 C). If the initial 24 h curing is at 100 F (38 C), the 28-day compressive strength of the test specimens may be 10 to 15% lower than if cured at the required ASTM C 31/C 31M 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 fabrication, curing, and testing of the test specimens during hot weather is critical, and steps should be taken to ensure that the specified procedures are followed.

#### **1.2—Definition of hot weather**

**1.2.1** For the purpose of this report, hot weather is any 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;
- Wind speed; and
- Solar radiation.

**1.2.2** The effects of high air temperature, solar radiation, and low relative humidity may be more pronounced with increases in wind speed ([Fig. 2.1.5](#)). The potential problems of hot weather concreting may occur at any time of the year in warm tropical or arid climates, and generally occur during the summer season in other climates. Early cracking due to thermal shrinkage is generally more severe in the spring and fall. This is because the temperature differential for each 24 h period is greater during these times of the year. Precautionary measures required on a windy, sunny day will be more strict than those required on a calm, humid day, even if air temperatures are identical.

#### **1.3—Potential problems in hot weather**

**1.3.1** Potential problems for concrete in the freshly mixed state are likely to include:

- Increased water demand;
- Increased rate of slump loss and corresponding tendency to add water at the job site;
- Increased rate of setting, resulting in greater difficulty with handling, compacting, and finishing, and a greater risk of cold joints;
- Increased tendency for plastic-shrinkage cracking; and
- Increased difficulty in controlling entrained air content.

**1.3.2** Potential deficiencies to concrete in the hardened state may include:

- Decreased 28-day and later strengths resulting from

either higher water demand, higher concrete temperature, or both at time of placement or during the first several days;

- Increased tendency for drying shrinkage and differential thermal cracking from either cooling of the overall structure, or from temperature differentials within the cross section of the member;
- Decreased durability resulting from cracking;
- Greater variability of surface appearance, such as cold joints or color difference, due to different rates of hydration or different water-cementitious material ratios ( $w/cm$ );
- Increased potential for reinforcing steel corrosion—making possible the ingress of corrosive solutions; and
- Increased permeability as a result of high water content, inadequate curing, carbonation, lightweight aggregates, or improper matrix-aggregate proportions.

#### 1.4—Potential problems related to other factors

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

- Use of cements with increased rate of hydration;
- Use of high-compressive-strength concrete, which requires higher cement contents;
- Design of thin concrete sections with correspondingly greater percentages of steel, which complicate placing and consolidation of concrete;
- Economic necessity to continue work in extremely hot weather; and
- Use of shrinkage-compensating cement.

#### 1.5—Practices for hot weather concreting

Any damage to concrete caused by hot weather can never be fully alleviated. Good judgment is necessary to select the most appropriate compromise of quality, economy, and practicability. The procedures selected will depend on: type of construction; characteristics of the materials being used; and experience of the local industry in dealing with high ambient temperature, high concrete temperatures, low relative humidity, wind speed, and solar radiation.

The most serious difficulties occur when personnel placing the concrete lack experience in constructing under hot weather conditions or in doing the particular 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 detailed procedures for mixing, placing, protection, curing, temperature monitoring, 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. Methods to control cracking include: proper use of joints, increased amounts of reinforcing steel or fibers, limits on concrete temperature, reduced cement content, low-heat-of-hydration cement, increased form-stripping time, and selection and dosage of appropriate chemical and mineral admixtures.

The following list of practices and measures to reduce or avoid the potential problems of hot weather concreting are discussed in detail in Chapters 2, 3, and 4:

- Select concrete materials and proportions with satisfactory records in hot weather conditions;
- Cool the concrete;
- Use a concrete consistency that permits rapid placement and effective consolidation;
- Minimize the time to transport, place, consolidate, and finish the concrete;
- Plan the job to avoid adverse exposure of the concrete to the environment; schedule placing operations during times of the day or night when weather conditions are favorable;
- Protect the concrete from moisture loss during placing and curing periods; and
- Schedule a preplacement conference to discuss the requirements of hot weather concreting.

## CHAPTER 2—EFFECTS OF HOT WEATHER ON CONCRETE PROPERTIES

### 2.1—General

**2.1.1** Properties of concrete that make it an excellent construction material can be affected adversely by hot weather, as defined in [Chapter 1](#). Harmful effects are minimized by control procedures outlined in this report. Strength, impermeability, dimensional stability, and resistance of the concrete to weathering, wear, and chemical attack all depend on the following factors: selection and proper control of materials and mixture proportioning; initial concrete temperature; wind speed; solar radiation; ambient temperature; and humidity condition during the placing and curing period.

**2.1.2** 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. The data in [Fig. 2.1.2](#) shows that with increasing curing temperatures, 1-day strength will increase, and 28-day strength decreases (Klieger 1958; Verbeck and Helmuth 1968). Some researchers conclude that a relatively more uniform microstructure of the hydrated cement paste can account for higher strength of concrete mixtures cast and cured at lower temperatures (Mehta 1986).

**2.1.3** Laboratory tests have demonstrated the adverse effects of high temperatures with a lack of proper curing on concrete strength (Bloem 1954). Specimens molded and cured in air at 73 F (23 C), 60% relative humidity and at 100 F (38 C), 25% relative humidity produced strengths of only 73 and 62%, respectively, of that obtained for standard specimens moist-cured at 73 F (23 C) for 28 days. The longer the delay between casting the cylinders and placing into standard moist storage, the greater the strength reduction. The data illustrate that inadequate curing in combination with high placement temperatures impairs the hydration process and reduces strength. The tests were made on plain concrete without admixtures or pozzolans that might have improved its performance at elevated temperatures. Other researchers determined that insufficient curing is more detrimental than

**Table 2.1.5—Typical concrete temperatures for various relative humidities potentially critical to plastic-shrinkage cracking**

Concrete temperature, F (C)	Air temperature, F (C)	Critical evaporation rate			
		0.2 lb/ft <sup>2</sup> /h (1.0 kg/m <sup>2</sup> /h)	0.15 lb/ft <sup>2</sup> /h (0.75 kg/m <sup>2</sup> /h)	0.10 lb/ft <sup>2</sup> /h (0.50 kg/m <sup>2</sup> /h)	0.05 lb/ft <sup>2</sup> /h (0.25 kg/m <sup>2</sup> /h)
		Relative humidity, %*			
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, % which evaporation rate will exceed the critical values shown, assuming air temperature is 10 F (6 C) cooler than 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 NRMCA-PCA nomograph (Fig. 2.1.5), results rounded to nearest 5%.

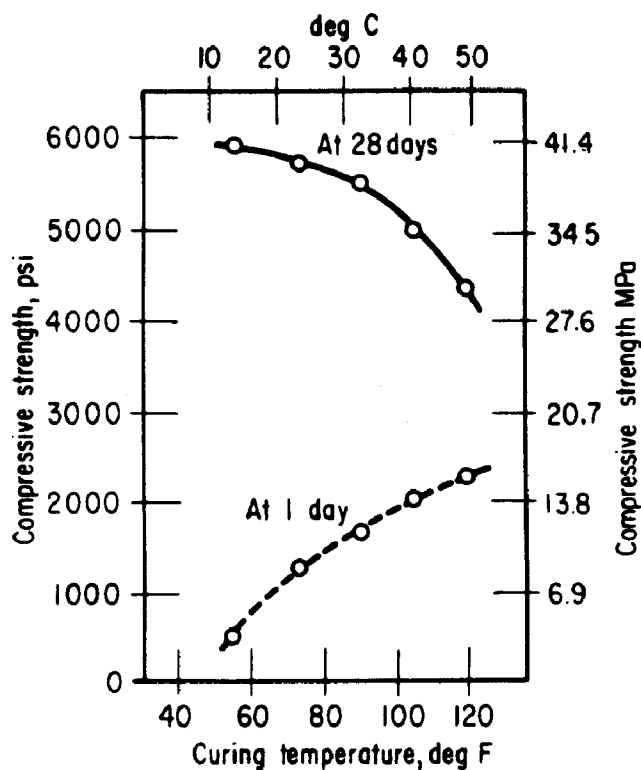


Fig 2.1.2—Effects of curing temperature on compressive strength of concrete (Verbeck and Helmuth 1968).

high temperatures (Cebeci 1986), and also that required strength levels can be maintained by the proper use of either chemical or mineral admixtures are used in the concrete (Gaynor et al 1985; Mittelacher 1985 & 1992).

**2.1.4 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, and may develop in other climates 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 water rises to the surface of recently placed concrete by bleeding. A method to estimate

evaporation rate is given in Section 5.1.3. High concrete temperatures, high wind speed, and low humidity, alone or in combination, cause rapid evaporation of surface water. The rate of 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 and finishing. Because surface drying is initiated when evaporation rate exceeds bleeding rate, the probability of plastic-shrinkage cracking therefore increases whenever the environmental conditions increase evaporation, or when the concrete has a reduced bleeding rate. For example, concrete mixtures incorporating 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).

**2.1.5 Plastic-shrinkage cracking** is seldom a problem in hot-humid climates where relative humidity is rarely less than 80%. Table 2.1.5 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.

The nomograph in Fig. 2.1.5 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 1997). The method is therefore the 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<sup>2</sup>/h (1.0 kg/m<sup>2</sup>/h), the method has been shown to be in good agreement with water loss measurements, as long as the temperature, humidity, and wind speed have been measured as

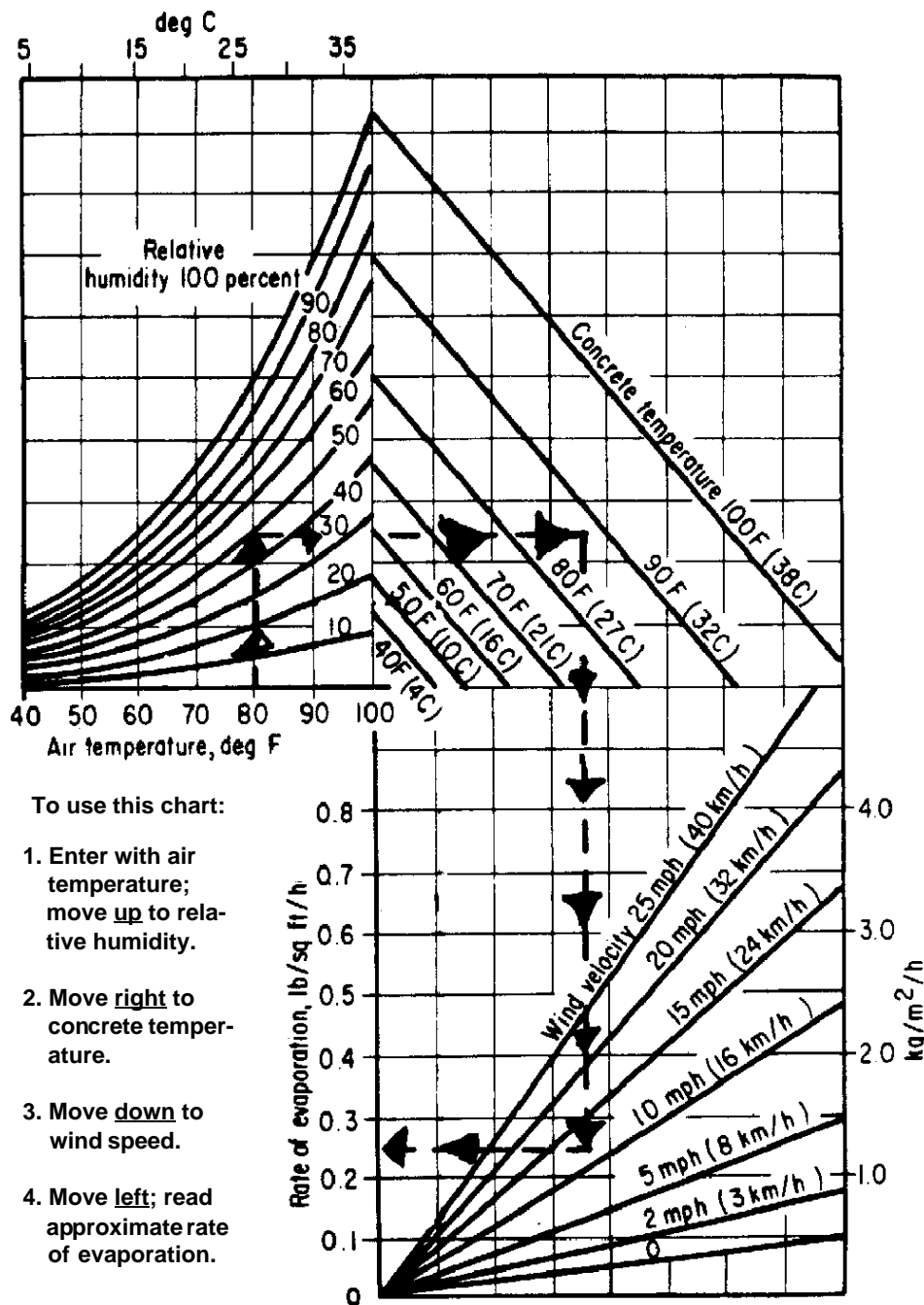


Fig. 2.1.5—Effect of concrete and air temperatures, relative humidity, and wind speed on the rate of evaporation of surface moisture from concrete. This chart provides a graphic method of estimating the loss of surface moisture for various weather conditions. To use this chart, follow the four steps outlined above. If the rate of evaporation approaches 0.2 lb/ft<sup>2</sup>/h (1 kg/m<sup>2</sup>/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. (510 mm) 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 (PCA Journal 1957).

described in the text below Fig. 2.1.5. It is especially critical that wind speed be monitored at 20 in. (0.5 m) above the evaporating surface. This is 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. Note also that wind speed varies tremendously over

time, and estimates should not be based on transient gusts of wind. Use of Fig. 2.1.5 provides evaporation rate estimates based on environmental factors of temperature, humidity, and wind speed that contribute to 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



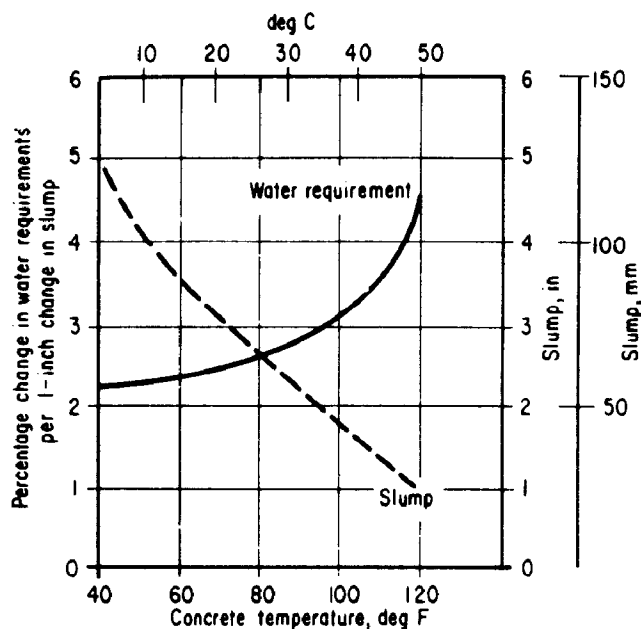


Fig. 2.2.1(a)—Effect of concrete temperature on slump and on water required to change slump (average data for Type I and II cements) (Klieger 1958).

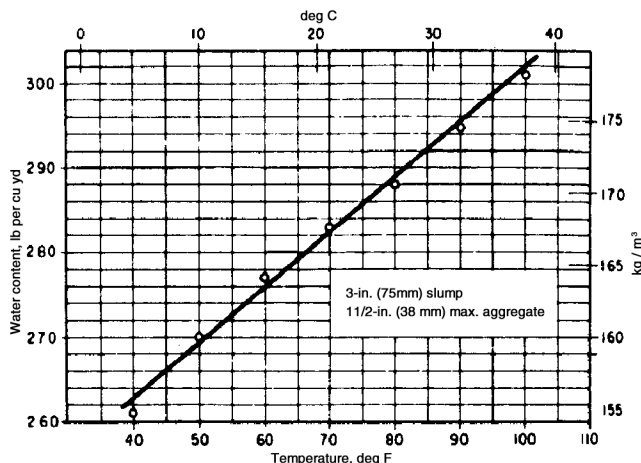


Fig. 2.2.1(b)—Effect of temperature increase on the water requirement of concrete (U.S. Bureau of Reclamation 1975).

(21 C) placed at an air temperature of 70 F (21 C), with a relative humidity of 50% 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.

**2.1.6** When evaporation rate is expected to approach the bleeding rate of the concrete, precautions should be taken, as explained in detail in **Chapter 4**. Because bleeding rates vary from zero to over 0.2 lb/ft<sup>2</sup>/h (1.0 kg/m<sup>2</sup>/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<sup>2</sup>/h (1.0 kg/m<sup>2</sup>/h). More recent experience with bridge deck overlays containing silica fume has led to specified allowable evaporation rates of only 0.05 lb/ft<sup>2</sup>/h (0.025 kg/m<sup>2</sup>/h) (Virginia Department Of Transportation). Construction specifications for the State of New York and the City of Cincinnati are intermediate evaporation rates of 0.15

and 0.10 lb/ft<sup>2</sup>/h (0.75 and 0.50 kg/m<sup>2</sup>/h), respectively. The probability for plastic-shrinkage cracks to occur may 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 may thereby contribute to a cracking tendency (ACI 226.3R). Plastic-shrinkage cracks are difficult to close once they have occurred (see Section 4.3.5).

## 2.2—Temperature of concrete

**2.2.1** Unless measures are taken to control concrete performance at elevated temperatures, by the selection of suitable materials and proportions as outlined in Sections 2.3 through 2.9, increases in concrete temperature will have the following adverse effects. Other adverse effects are listed in **Section 1.3**.

- The amount of the water required to produce a given slump increases with the time. For constant mixing time, the amount of water required to produce a given slump also increases with the temperature, as shown in Fig. 2.2.1(a) and 2.2.1(b);
- Increased water content will create a decrease in strength and durability, if the quantity of cementitious material is not increased proportionately;
- Slump loss will be evident earlier after initial mixing and at a more rapid rate, and may cause difficulties with handling and placing operations;
- In an arid climate, plastic-shrinkage cracks are more probable;
- In sections of large dimensions, there will be an increased rate of hydration and heat evolution that will increase differences in temperature between the interior and the exterior concrete. This may cause thermal cracking (ACI 207.1R);
- Early curing is critical and lack of it increasingly detrimental as temperatures rise.

## 2.3—Ambient conditions

**2.3.1** In the more general types of hot weather construction (as defined in **Section 1.2**), it is impractical to recommend a maximum ambient or concrete temperature because the humidity and wind speed may be low, permitting higher ambient and concrete temperatures. A maximum ambient or concrete temperature that will serve a specific case may be unrealistic in others. Accordingly, the committee can only provide information about the effects of higher temperatures in concrete as mentioned in Sections 1.3 and 2.2.1, and advise that at some 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. Practices for hot weather concreting should be discussed during the preplacement conference.

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 C 192. Procedures for testing of concrete batches at temperatures higher than approximately 70 F (21 C) are given in Section 2.9.

## 2.4—Water requirements

**2.4.1** 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. Fig. 2.2.1(b) illustrates the possible effect of concrete temperature on water requirements. Unless the amount of cementitious material is increased proportionately, the extra water increases the water-cementitious material ratio and will decrease the strength, durability, watertightness, and other related properties of the concrete. This extra water must be accounted for during mix proportioning. Although pertinent to concrete placed under all conditions, this points to the special need to control the use of additional water in concrete placed under hot weather conditions; see Section 2.3.1.

**2.4.2** Fig. 2.2.1(a) 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 may be expected to decrease the slump by about 1 in. (25 mm). Fig. 2.2.1(a) also illustrates changes in water requirement that may be necessary to produce a 1 in. (25 mm) increase in slump at various temperature levels. For 70 F (21 C) concrete, about 2-1/2% more water is required to increase slump 1 in. (25 mm); for 120 F (50 C) concrete, 4-1/2% more water is needed for the 1 in. slump increase. The original mixing water required to change slump may be less if a water-reducing, midrange water-reducing, or high-range water-reducing admixture is used.

**2.4.3** Drying shrinkage generally increases with total water content (Portland Cement Association Design and Control of Concrete Mixtures 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.

**2.4.4** Because water has a specific heat of about 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. The temperature of water is easier to control than that of the other components. Even though water is used in smaller quantities than the other ingredients, cooled water will reduce the concrete placing temperature, but usually by not more than approximately 8 F (4.5 C) (Fig. 2.4.4). 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. In general, lowering the temperature of the batch water by 3.5 to 4 F (2.0 to 2.2 C) will reduce the concrete temperature approximately 1 F (0.5 C). Efforts should therefore be made to obtain cold water. To keep it cold, tanks, pipes, or trucks used for storing or transporting water should be either insulated, painted white, or both. Water can be cooled to as low as 33 F

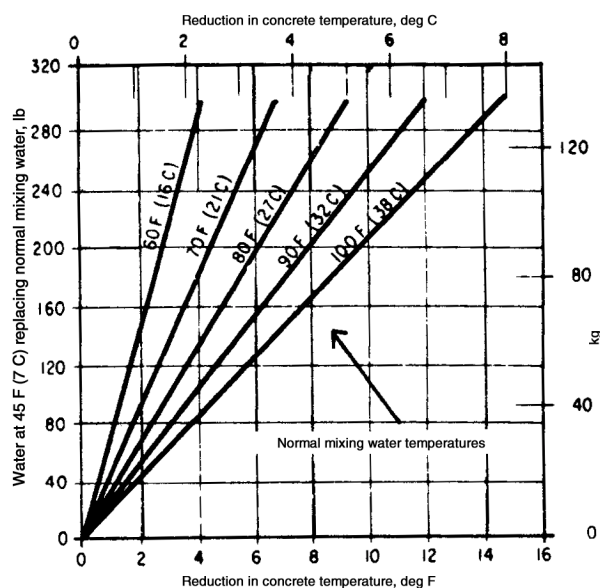


Fig. 2.4.4—General effects of cooled mixing water on concrete temperature (National Ready Mixed Concrete Association 1962).

(1 C) using water chillers, ice, heat pump technology, or liquid nitrogen. These methods and their effectiveness are discussed further.

**2.4.5** Using ice as part of the mixing water has remained a major means of reducing 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. For maximum effectiveness, the ice should not be allowed to melt before it is placed in the mixer in contact with other ingredients, however, but it must melt completely prior to the completion of mixing of the concrete. For a more rapid blending of materials at the beginning of mixing, not all of the available batch water should be added in the form of ice. Its quantity may have to be limited to approximately 75% of the batch water requirement. 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. Fig. 2.4.5 illustrates 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 is melted completely. Crushed ice should be stored at a temperature that will prevent lumps from forming by refreezing of particles.

**2.4.6** The temperature reduction can also be estimated by using Eq. (A-4) or (A-5) 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 may be the most expedient means. See Appendix B for additional information. Liquid injected nitrogen does not affect the mixing water requirement except by reducing concrete temperature.

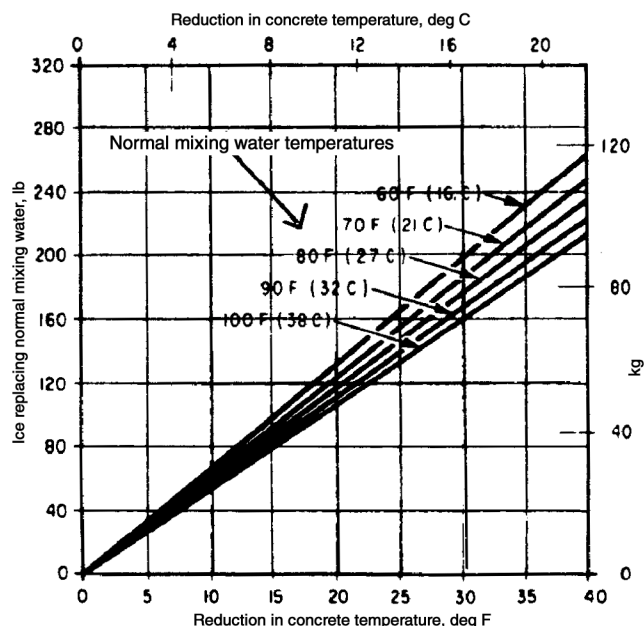


Fig. 2.4.5—General effects of ice in mixing water on concrete temperature. Temperatures are normal mixing water temperatures (National Ready Mixed Concrete Association 1962).

## 2.5—Effect of cement

**2.5.1** High concrete temperature increases the rate of hydration (Fig. 2.5.2). As a result, concrete stiffens more rapidly and requires more water to produce or maintain the desired slump. The higher water content will cause strength loss and increase the cracking tendency of the concrete unless offset by measures described in Sections 2.6.1 and 2.7.

**2.5.2** Selection of a particular cement may have a decided effect on the hot weather performance of concrete, as illustrated in Fig. 2.5.2. Although the curves are based on limited data from mixtures using 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 h 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). Fig. 2.5.2 is a good example of the difficulty of predicting performance of concrete at different temperatures. In general, use of a normally slower-setting Type II portland cement (ASTM C 150) or Type IP or IS blended cement (ASTM C 595) may improve the handling characteristics of concrete in hot weather (ACI 225R). Concrete containing the slower setting cements will be more likely to exhibit plastic-shrinkage cracking.

**2.5.3** 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 will be less thermal expansion, and the risk of thermal cracking upon cooling of the concrete will be reduced. This is an important consideration for slabs, walls, and mass concretes, as discussed in ACI 207.1R and ACI 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 that

required to provide strength and durability. Concrete mixtures that obtain high strength at an early age will develop high concrete temperature during initial curing. These concrete mixtures should be provided thermal protection to ensure gradual cooling at a rate that will not cause them to crack; see Section 4.4.1.

**2.5.4** Cement may be 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 will consist of approximately 10 to 15% cement. This will increase concrete temperature approximately 1 F (0.5 C) for each 8 F (4 C) increase in cement temperature.

## 2.6—Supplementary cementitious materials

**2.6.1** Materials in this category include fly ash and other pozzolans (ASTM C 618) and ground granulated blast-furnace slag (ASTM C 989). Each are widely used as partial replacements for portland cement; they may impart a slower rate of setting and of early strength gain to the concrete, which is desirable in hot weather concreting, as explained in Section 2.5.2. Faster setting cements or cements causing a rapid slump loss in hot weather may perform satisfactorily in combination with these materials (Gaynor et al 1985). The use of fly ash may reduce the rate of slump loss of concrete under hot weather conditions (Ravina 1984; Gaynor et al 1985).

## 2.7—Chemical admixtures

**2.7.1** Various types of chemical admixtures (ASTM C 494) have been found beneficial in offsetting some of the undesirable characteristics of concrete placed during periods of high ambient temperatures (see also ACI 212.3R). The benefits may 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 with which they are used in the concrete. Admixtures without a history of satisfactory performance at the expected hot weather conditions should be evaluated before their use, as explained in Section 2.7.5. Chemical admixtures affect the properties of concrete as described in the following.

**2.7.2** Retarding admixtures meeting ASTM C 494, 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 may be used to obtain a uniform time of setting. Their water-reducing properties largely offset the higher water demand resulting from increases in concrete temperature. Because water-reducing retarders 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 and 1992). Compared with concrete without admixture, a concrete mixture that uses a water-reducing and retarding admixture may have a higher rate of slump loss. The net wa-



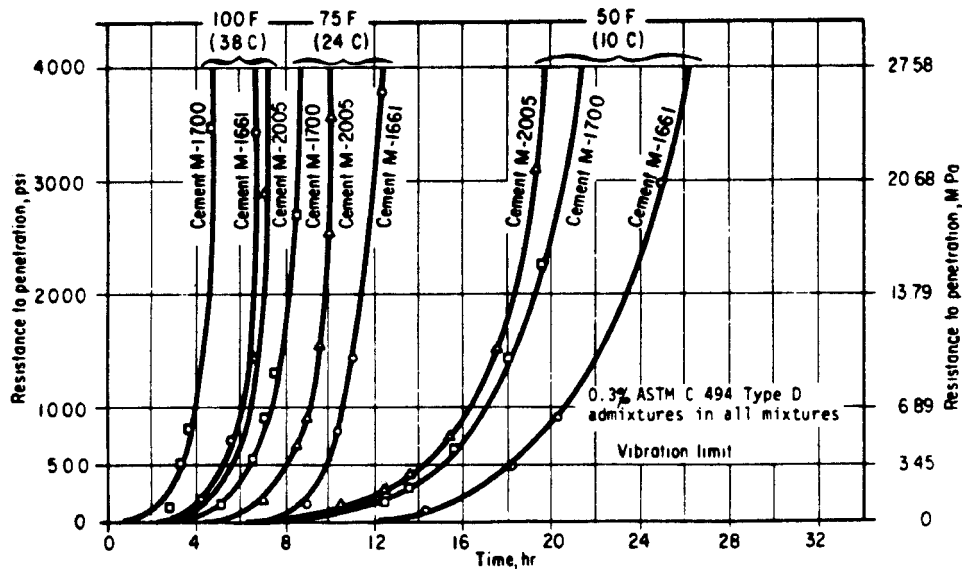


Fig 2.5.2—Effect of temperature and brand of cement on setting time characteristics of concrete mortars (Tuthill and Cordon 1955).

ter reduction and other benefits remain substantial even after the initial slump is increased to compensate for slump loss.

**2.7.3** Admixtures of the hydroxylated carboxylic acid type (ACI 212.3R, Class 3) and some types meeting ASTM C 494, Type D requirements may increase the early bleeding and rate of bleeding of concrete. This admixture-induced early bleeding may be helpful in preventing drying of the surface of concrete placed at high ambient temperature and low humidity. Concrete that is prone to bleeding generally should be reconsolidated after most of the bleeding has taken place. Otherwise, differential settling may occur that 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 hot weather. If the admixture reduces the tensile strength and tensile strain capacity, however, plastic-shrinkage tendencies may be increased (Ravina and Shalon 1968). Other admixtures (ACI 212.3R, Classes 1 and 2) may reduce bleeding rate. If drying conditions are such that crusting of the surface blocks bleed water from reaching the surface, continued bleeding may cause scaling. 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.

**2.7.4** Some high-range, water-reducing and retarding admixtures (ASTM C 494, Type G), and plasticizing and retarding admixtures (ASTM C 1017, Type II), often referred to as superplasticizers, 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 (see ASTM STP 169C and 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 may 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 admixture and with the same cement content. Certain products may cause significant bleeding, which may be beneficial in many instances, but may require some precautions in others (see Section 2.7.3). Air-content tests will be needed before placement to assure maintenance of proper air content. Assurance also may be needed that the air-void system is not impaired if it is required for the freezing and thawing resistance of the concrete. This can be determined by requiring hardened air analysis or ASTM C 666 freezing and thawing testing. Some high-range water-reducing retarders can maintain the necessary slump for extended periods at elevated concrete temperatures (Colleparidi et al 1979; Hampton 1981; Guennewig 1988). These will be of particular benefit in the event of delayed placements or deliveries over greater distances. Other high-range water-reducing admixtures may 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 a couple of hours, followed by acceleration of strength gain.

**2.7.5** Since the early 1990s, the use of midrange water-reducing admixtures in hot weather has increased. Midrange water-reducing admixtures provide up to 15% water reduction, which is higher than conventional water-reducing admixtures, but lower water reduction than high-range water-reducing admixtures. Although at present there is no ASTM classification, midrange water-reducing admixtures comply with the requirements of ASTM C 494, Type A admixtures, and in some cases, Type F admixtures. These admixtures will not delay the setting time of the concrete significantly. At higher dosages, conventional water-reducing admixtures can achieve this water reduction, but with significant increase in the setting time of the concrete. The pumping and finishing characteristics of concrete containing midrange water-reducing admixtures are improved when

compared with concrete containing conventional Type A water reducers. The use of midrange water reducers is particularly beneficial in cases where aggregate properties contribute to poor workability or finishing difficulties. The surface appearance of concrete containing a midrange water reducer could be changed, thereby requiring a change of the timing of finishing operations. Also available are midrange water-reducing and retarding admixtures that comply with ASTM C 494 requirements for Type D admixtures.

**2.7.6** The use of extended set-control admixtures to stop the hydration process of freshly mixed concrete (freshly batched or returned plastic concrete that normally would be disposed), and concrete residue (washwater) in ready-mix truck drums has gained increased acceptance in hot weather environments since their introduction in 1986. Some extended set-control admixtures comply with ASTM C 494 requirements for Type B, retarding admixtures, and Type D, water-reducing and retarding mixtures. 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 only act on the silicate phases, which extend (not stop) the hydration process. The technology of extended set-control admixtures may 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 incorporating project time requirements in this way ensuring that the concrete will achieve the required setting time. Additional admixtures are not required to restart hydration.

**2.7.7** The qualifying requirements of ASTM C 494 afford a valuable screening procedure for the selection of admixture products. Admixtures without a performance history pertaining to the concrete material selected for the work should be first evaluated in laboratory trial batches at the expected high job temperature, using one of the procedures described in Section 2.9. Some high-range, water-reducing retarders may not 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 admixture should be evaluated for consistency of performance in regard to 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 may influence selection of an admixture and its dosage more than properties usually covered by most specifications.

## 2.8—Aggregates

**2.8.1** Aggregates are the major constituent of concrete, as they account for 60 to 80% of the volume of normalweight concrete used in most structures. Therefore, the properties of

the aggregate affect the quality of concrete significantly. The size, shape, and grading of the aggregate are three of the principal factors that affect the amount of water required to produce concrete at a given slump. Aggregate properties desirable in hot weather concreting include the following:

- Gradation, particle shape, and the absence of undersized material are very important in minimizing water demand (ACI 221R). Crushed coarse aggregate also contributes to higher water demand, but is reported to provide better resistance to cracking than rounded gravels (ACI 224R). The blending of three or more aggregate sizes may reduce the mixing water requirements and improve workability at a given slump (Shilstone, Sr. and Shilstone, Jr. 1993).

**2.8.2** With coarse aggregate being the ingredient of greatest mass in concrete, 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 will lower the concrete temperature 1 F (0.5 C). Cooling the coarse aggregate may be an effective supplementary means to achieve desired lower concrete temperature (see [Appendix B](#)).

## 2.9—Proportioning

**2.9.1** Mixture proportions may be established or adjusted on the basis of field-performance records in accordance with ACI 318/318R (ACI 318/318RM), provided the records indicate the effect of expected seasonal temperatures and delivery times.

**2.9.2** 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 and 211.2). 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 ground granulated blast-furnace slag, 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 if longer delivery periods are anticipated. Unless required otherwise, concrete should be proportioned for a slump of not less than 3 in. (75 mm) to permit prompt placement and effective consolidation in the form.

**2.9.3** The performance of the concrete mixtures proposed for the work 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 C 192. 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 with consideration of using a mixing and agitating period longer than that required in ASTM C 192 to help define the performance to be expected.

**2.9.4** In determining mixture proportions using laboratory trial batches, a procedure for estimating the slump loss dur-

ing the period between first mixing of the concrete and its placement in the form is suggested in Procedures A and B, below, adopted from ACI 223, Section 4.5.2 on shrinkage-compensating concrete. These procedures from ACI 223 were found to produce a rate of slump loss similar to that expected for a 30 to 40 min delivery time.

*Procedure A—*

1. Prepare the batch using ASTM C 192 procedures, but add 10% additional water over that normally required;
2. Mix initially in accordance with ASTM C 192 (3 min mixing followed by a 3 min rest and 2 min remixing);
3. Determine the slump and record as initial slump;
4. Continue mixing for 15 min;
5. Determine the slump and record as estimated placement slump. Experience has shown this slump correlates with that expected for 30 to 40 min 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; and
6. Determine other properties of fresh concrete (temperature, air content, unit weight), and mold strength test specimens.

*Procedure B—*

1. Prepare the batch using ASTM C 192 procedures for the specified slump;
2. Mix in accordance with ASTM C 192 (3 min mixing, 3 min rest, and 2 min remixing) and confirm the slump;
3. Stop the mixer and cover the batch with wet burlap;
4. After 20 min, remix 2 min, 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; and
5. Determine other properties of fresh concrete (temperature, air content, unit weight), and mold-strength test specimens.

**2.9.5** As an alternative method, use of full-size production batches may be considered for verification of mixture proportions, provided the expected high temperature levels of the concrete can be attained. This may be the preferred method when using admixtures selected for extended slump retention. It requires careful recording of batch quantities at the plant and of water added for slump adjustment before sampling. Sampling procedures of ASTM C 172 should be strictly observed.

## CHAPTER 3—PRODUCTION AND DELIVERY

### 3.1—General

Production facilities and procedures should be capable of providing the required quality 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 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. In hot weather concreting operations, concrete placements may be scheduled at times other than during daylight hours, such

as during the coolest part of the morning. Night-time production requires good planning and good lighting.

### 3.2—Temperature control of concrete

**3.2.1** Concrete can be produced in hot weather without maximum limits on placing temperature and will perform satisfactorily if proper precautions are observed in proportioning, production, delivery, placing, and curing. As part of these precautions, an effort should be made to keep the concrete temperature as low as practical. Using the relationships given in [Appendix A](#), it can be shown, for example, that the temperature of concrete of usual proportions can be reduced by 1 F (0.5 C) if any of the following reductions are made in material temperatures:

- 8 F (4 C) reduction in cement temperature;
- 4 F (2 C) reduction in water temperature; or
- 2 F (1 C) reduction in the temperature of the aggregates.

**3.2.2** [Fig. 3.2.2](#) 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, and sprinkling and fog spraying of coarse aggregates stock-piles under arid conditions will help. Sprinkling of coarse aggregates with cool water can reduce 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 will have greater effects in areas that have low relative humidity. Wetting of aggregates, however, tends to cause variations in surface moisture and thereby complicates slump control. Above-ground storage tanks for mixing water should be provided with shade and thermal insulation. Silos and bins will absorb less heat if coated with heat-reflective paints. Painting mixer surfaces white to minimize solar heat gain will be of some help. Based on 1 h 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. If an empty mixer drum stands in the sun for an extended period before concrete is batched, the heat stored in the metal drum would produce concrete temperatures 0.5 to 1 F (0.3 to 0.5 C) lower for a white mixer drum 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 can be expected to be of only marginal benefit.

**3.2.3** 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 assured for each placement.

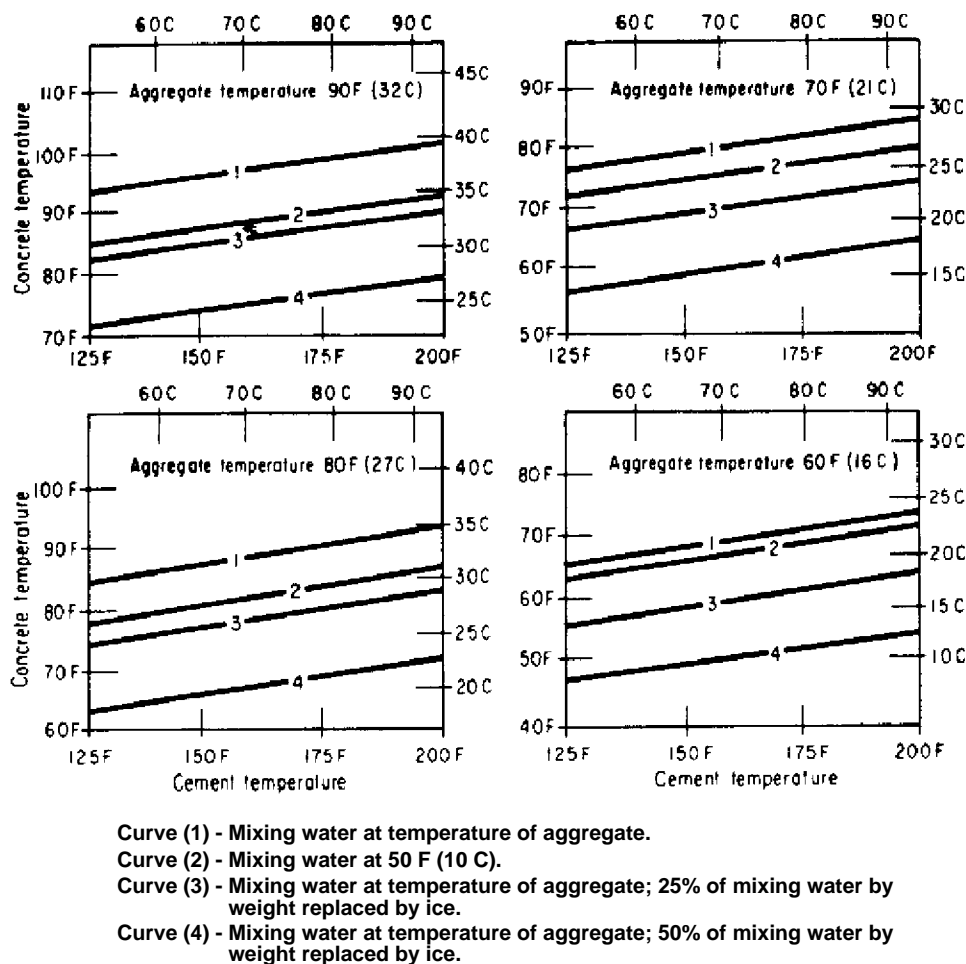


Fig. 3.2.2—Influence of temperature of concrete ingredients on concrete temperature. Calculated from equations in Appendix A.

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. 3.2.2.

### 3.3—Batching and mixing

**3.3.1** Batching and mixing is described in ACI 304R. Procedures under hot weather conditions are no different from good practices under normal weather conditions. Producing concrete of the correct slump and other specified properties to confirm with applicable specifications is essential. An interruption in the concrete placement due to rejection may cause the formation of a cold joint or serious problems in finishing. Testing of concrete must be diligent and accurate so that results represent the true condition of the concrete.

**3.3.2** For truck-mixed concrete, initial mixing of approximately 70 revolutions at the batch plant prior to transporting will allow 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. Slump can easily change due to minor changes in materials and concrete characteristics. For example, an undetected change of only 1.0%

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% in the determination of aggregate moisture complicates moisture control, even with advanced systems. Operators often batch concrete in a drier condition than desired to avoid producing a slump higher than specified; a small water addition may be needed at the job site.

**3.3.3** Hot weather conditions and extended hauling time may 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 may not, however, contribute to concrete uniformity between loads. These methods may, 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 some effective retarding admixtures at appropriate dosages, preferably in combination with cementitious material of slow-setting characteristics, concrete can be maintained in a placeable condition for extended periods even in hot weather (see [Section 2.7](#)). 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<sup>3</sup> (5 to 10 L/m<sup>3</sup>), after the concrete has been mixed for several minutes. These 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 midrange water-reducing or high-range water-reducing admixtures is recommended to increase the concrete slump.

**3.3.4** Under hot weather conditions, the amount of mixing at mixing speed of the mixer should be held to a minimum to avoid any 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 min). The drum should not be stopped for extended periods of time. There is potential for false setting problems causing the concrete to stiffen rapidly or set in the drum, or for flattening of the mixer rollers.

**3.3.5** Specifications governing the total number of revolutions of the drum usually set a limit of 300 revolutions for truck mixers. This limit should be waived for conditions that require further thorough mixing of the concrete:

- Separate addition of high-range, water-reducing admixtures;
- Direct addition of liquid injected nitrogen into the mixer as a means of lowering the concrete temperature; and
- If the concrete retains its workability without the addition of water.

### 3.4—Delivery

Cement hydration, temperature rise, slump loss, aggregate grinding, and either loss or, occasionally, gain of air content all occur with the passage of time while the concrete is in the mixer; thus, the period between start of mixing to start of placement of the concrete should be minimized. Coordinating the dispatching of mixer trucks with the rate of concrete placement avoids delays in arrival or waiting periods until discharge. On major concrete placements, provisions should be made to have good communications between the job site and concrete-production facility. Major placements should be scheduled during periods of lower urban traffic loads. When placement is slow, consideration should be given to reducing load size, using set-retarding admixture, or using cooled concrete.

### 3.5—Slump adjustment

Fresh concrete is subject to slump loss with time, whether it is used in moderate or hot weather. With given materials and mixture proportions, the slump change characteristics between plant and job site should be established. With the limitations on accurately predicting slump, as explained in [Section 3.3.2](#), uncertainty in traffic, and the timing of placing operations, operators need to batch concrete in a drier condition to avoid a slump higher than specified. If, on arrival at the job site, the slump is less than the specified maximum, additional water may be added if the maximum

allowable water content is not exceeded. When water is added to bring the slump within required limits, the drum or blades must be turned an additional 30 revolutions or more, if necessary, at mixing speed. For expeditious placement and effective consolidation, structural concrete should have a minimum slump of 3 or 4 in. (75 or 100 mm). Slump increases should be allowed when chemical admixtures are used, providing the admixture-treated concrete has the same or lower water-cementitious materials ratio (*w/cm*) and does not exhibit segregation potential.

### 3.6—Properties of concrete mixtures

The proposed mixtures should be suitable for expected job conditions. This is particularly important when there are no limits on placing temperatures, as is the case in most general construction in the warmer regions. Use of cements or cementitious materials that perform well under hot weather conditions, in combination with water-reducing and retarding admixtures, can provide concrete of required properties (Mittelacher 1985). When using high-range, water-reducing and retarding admixtures, products should be selected that provided extended slump retention in hot weather (Collepari 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, with the lower layer still in a plastic condition. The type of adjustment depends on local climatic conditions, timing of placements, and concrete temperatures. A change in admixture dosage or formulation can often provide the desired setting time.

### 3.7—Retempering

Retempering is defined as “additions of water and remixing of concrete, or mortar which has lost enough workability to become unplaceable or unsaleable” (ACI 116R). 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 in excess of 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, may be very effective to maintain workability.

## CHAPTER 4—PLACING AND CURING

### 4.1—General

**4.1.1** The requirements for good results in hot weather concrete placing and curing are no different than in other seasons. The same necessities exist:

- Concrete be handled and transported with a minimum of segregation and slump loss;
- Concrete be placed where it is to remain;
- Concrete be placed in layers shallow enough to assure vibration well into the layer below and that the elapsed time between layers be minimized to avoid cold joints;
- Construction joints outlined in ACI 224.3R be made on sound, clean concrete;
- Finishing operations and their timing be guided only by

the readiness of the concrete for them, and nothing else; and

- Curing be conducted so that at no time during the prescribed period will the concrete lack ample moisture and temperature control to permit full development of its potential strength and durability.

**4.1.2** Details of placing, consolidation, and curing procedures are described in ACI 304R, 308R, and 309R. It is the purpose of this chapter to point out the factors peculiar to hot weather that can affect these operations and the resulting concrete and to recommend what should be done to prevent or offset their influence.

## 4.2—Preparations for placing and curing

**4.2.1** *Planning hot weather placements*—Prior to the start of the project, plans should be made for minimizing the exposure of the concrete to adverse conditions. Whenever possible, placing of slabs should be scheduled after roof structure and walls are in place to minimize problems associated with drying winds and direct sunlight. This will also reduce thermal shock from rapid temperature drops caused by wide day and night temperature differences or cool rain on concrete heated by the sun earlier in the day.

Under hot weather conditions, scheduling concrete placements at other-than-normal hours may be advisable. Pertinent considerations include ease of handling and placing, and avoiding the risk of plastic-shrinkage and thermal cracking.

**4.2.2** *Preparing for ambient conditions*—Personnel in charge of concrete construction should be aware in advance of the damaging combinations of high air temperature, direct sunlight, drying winds, and high concrete temperature. Monitoring of local weather reports and routine recording of conditions at the site, including air temperature, sun exposure, relative humidity, and prevailing winds, can be conducted locally. These data, together with projected or actual concrete temperatures, enable supervisory personnel through reference to [Fig. 2.1.5](#) to determine and prepare the required protective measures. Equipment should also be available at the site for measuring the evaporation rate in accordance with [Section 5.1.3](#).

**4.2.3** *Expediting placements*—Preparations must be made to transport, place, consolidate, and finish the concrete at the fastest possible rate. Delivery of concrete to the job should be scheduled so it will be placed promptly on arrival, particularly the first batch. Many concrete placements get off to a bad start because the concrete was ordered before the job was ready and slump control was lost at this most critical time. Traffic arrangements at the site should ensure easy access of delivery units to the unloading points over stable roadways. Site traffic should be coordinated for a quick turnaround of concrete mixer trucks. If possible, large or critical placements should be scheduled during periods of low urban traffic loads.

**4.2.4** *Placing equipment*—Equipment for placing the concrete shall be of suitable design and have ample capacity to perform its functions efficiently. All equipment should have adequate power for the work and be in first-class operating condition. Breakdowns or delays that stop or slow the place-

ment can seriously affect the quality and appearance of the work. Arrangements should be made for readily available backup equipment. Concrete pumps, if used, must be capable of pumping the specified class of concrete through the length of line and elevation at required rates per h. If 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 assure that concrete is charged into buckets only if 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 placing it into the form. To minimize the heat gain of the concrete during placement, delivery units, conveyors, pumps, and pump lines should be kept in the shade if possible. In addition, pump lines should be painted white. Lines can also be cooled by covering with damp burlap, kept wet with a soaker hose, or similar means.

**4.2.5** *Consolidation equipment*—There should be ample vibration equipment and manpower to consolidate the concrete immediately as it is received in the form. Procedures and equipment are described in ACI 309R. Provision should be made for an ample number of standby vibrators—at least one standby for each three vibrators in use. On sites subject to occasional power outages, portable generators should be available for uninterrupted vibrator operation. Apart from the unsightliness of poorly consolidated concrete, insufficient compaction in the form may seriously impair the durability and structural performance of reinforced concrete.

**4.2.6** *Preparations for protecting and curing the concrete*—Ample water should be available at the project site for moistening the subgrade, as well as for fogging forms and reinforcement prior to concrete placement, and for moist curing if applicable. 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 may be a practical means for fogging on smaller jobs. 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 compounds for applying temporary moisture-retaining films should be available to reduce evaporation from flatwork between finishing passes. If concrete placed under hot weather conditions is exposed to rapid temperature drops, thermal protection should be provided to protect the concrete against thermal-shrinkage cracking. Finally, curing materials should be readily available at the project site to permit prompt protection of all exposed surfaces from premature drying upon completion of the placement.

**4.2.7** *Preparing incidental work*—Due to faster setting and hardening of the concrete in hot weather, the timing of various final operations as saw-cutting joints and applying surface retarders becomes more critical; therefore, these operations must be planned in advance. Plans should be made for the timely sawing of contraction joints in flatwork to minimize cracking due to excessive tensile stresses. Typically, joints that are cut using the conventional wet or dry process

are made within 4 to 12 h after the slab has been finished; 4 h in hot weather to 12 h in cold weather. For early entry dry-cut saws, the waiting period will typically vary from 1 h in hot weather to 4 h in cold weather (ACI 302.1R).

### 4.3—Placement and finishing

**4.3.1 General**—Speed-up of placement and finishing materially reduces hot weather difficulties. Delays increase slump loss and invite the addition of water to offset it. Each operation in finishing should be carried out promptly when the concrete is ready for it. The concrete should not be placed faster than it can be properly consolidated and finished. If the placing rate is not coordinated with the available work force and equipment, the quality of the work will be marred by cold joints, poor consolidation, and uneven surface finishes.

**4.3.2 Placing formed concrete**—In hot weather, it is usually necessary to place concrete in shallower layers than those used in moderate weather to assure coverage of the lower layer while it will still respond readily to vibration. The interval between monolithic wall and deck placements becomes very short in hot weather. This interval may be extended by the judicious use of set-retarding admixtures.

**4.3.3 Placement of flatwork**—During the depositing of concrete for flatwork on the ground, the subgrade should be moist, yet free of standing water and soft spots. In placing concreting slabs of any kind, it may be necessary in hot weather to keep the operation confined to a small area and to proceed on a front having a minimum amount of exposed surface to which concrete is to be 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) must be avoided. Other means of reducing moisture loss include spreading and removing impervious sheeting or application of sprayable moisture-retaining (monomolecular) films one or more times as needed, between the various finishing operations. Finishing of flatwork should commence 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 may be reduced. Contact the product manufacturer for information on proper application and dosage. These procedures may cause a slight increase of the concrete temperature in place 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).

**4.3.4 Plastic-shrinkage cracks**—Without protection against moisture loss, plastic-shrinkage cracks may occur, as described in [Section 2.1.5](#). In relatively massive placements, revibration before floating can sometimes close this type of cracking. Before the concrete reaches final set, the 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 level finish.

It serves no lasting purpose to merely trowel a slurry over the cracks, because these are likely to reappear if not firmly closed and immediately covered to avoid evaporation.

### 4.4—Curing and protection

**4.4.1 General**—After completing placing and finishing operations, efforts must continue to protect the concrete from high temperature, direct sunlight, low humidity, and drying winds. If possible, the work should be kept in a uniformly moderate temperature condition to allow the concrete to develop its full strength potential. High initial curing temperatures are detrimental to the ultimate strength to a greater degree than high placing temperatures (Bloem 1954; Barnes et al 1977; Gaynor et al 1985). Procedures for keeping exposed surfaces from drying must be promptly commenced, with ample coverage and continued without interruption. Failure to do so may result in excessive shrinkage and cracking, and will impair the surface durability and strength of the concrete. Curing should be continued for at least the first 7 days. If a change in curing method is made during this period, it should be done only after the concrete is 3 days old. The concrete surface should not be permitted to become dry during the transition. The various methods of curing are described in ACI 308R. The concrete should also be protected against thermal-shrinkage cracking from rapid temperature drops, particularly during the first 24 h. This type of cracking is usually associated with a cooling rate of more than 5 F (3 C) per h, or more than 50 F (28 C) in a 24 h period for concrete with a least dimension less than about 12 in. (300 mm). Concrete exposed to rapid cooling has a lower tensile strain capacity and is more susceptible to cracking than concrete that is allowed to cool at a slower rate (ACI 207.4R). Hot weather patterns likely to cause thermal cracking include wide day and night temperature differences and cold rain. Under these conditions, the concrete should be protected by placing several layers of waterproof paper over the concrete, or by using other insulating methods and materials described in ACI 306R.

**4.4.2 Moist-curing of flatwork**—Of the different curing procedures, moist-curing is the best method for developing the strength of concrete and minimizing early drying shrinkage. It can be provided by ponding, covering with clean sand kept continuously wet, or continuous sprinkling. This will require an ample water supply and disposal of the runoff. When sprinkling is used, care must be taken that erosion of the surface does not occur. A more practical method of moist-curing is that of covering the prewetted concrete with impervious sheeting or application of absorptive mats or fabric kept continuously wet with a soaker hose or similar means. Suitable coverings are described in ACI 308R. These materials should be kept in contact with the concrete surface at all times. Alternate cycles of wetting and drying must be avoided because this may result in pattern cracking. The temperature of water used for curing must be as close as possible to that of the concrete to avoid thermal shock.

**4.4.3 Membrane curing of flatwork**—Use of liquid membrane-forming compounds is the most practical method of curing where job conditions are not favorable for moist-curing. The membranes restrict the loss of moisture from the



concrete, thereby allowing the development of strength, durability, and abrasion resistance of flatwork. On concrete surfaces exposed to the sun, heat reflecting white pigmented compounds should be used. The capability for moisture retention varies considerably between products. For use under hot weather conditions, a material should be selected that provides better moisture retention than required by ASTM C 309. It limits the moisture loss in a 72 h period to not more than 9 lb/yd<sup>3</sup> (0.55 kg/m<sup>3</sup>) when tested in accordance with ASTM C 156. Some agencies have set a more restrictive limit of 0.39 kg/m<sup>2</sup> of moisture loss in a 72 h period. On flatwork, application should be started immediately after disappearance of the surface water sheen after the final finishing pass. When applied by spraying, the spray nozzles should be held or positioned sufficiently close to the surface to assure the correct application rate and prevent wind-blown dispersion. Manual application should be in two passes, with the second pass proceeding at right angles to the first application. Most curing compounds should not be used on any surface against which additional concrete or other materials are to be bonded, unless the curing material will not reduce bond strength or unless removal of the curing material is assured before subsequent bonded construction.

**4.4.4 Curing of concrete in forms**—Forms should be covered and kept continuously moist during the early curing period. Formed concrete requires early access to ample external curing water for strength development. This is particularly important when using high-strength concrete having a *w/cm* less than approximately 0.40 (ACI 363R). The forms should be loosened as soon as this can be done without damage to the concrete, and provisions made for the curing water to run down inside them. Cracking may occur when the concrete cools rapidly from a high peak temperature and is restrained from contracting. In more massive members, and if the internal temperature rise cannot be controlled by available means, the concrete should be given thermal protection so that it will cool gradually at a rate that will not cause the concrete to crack. After form removal, form tie holes can be filled and any necessary repairs made by uncovering a small portion of the concrete at a time to carry on this work. These repairs should be completed in the first few days after stripping so the repairs and tie-hole fillings can cure with the surrounding concrete. At the end of the curing period (7 days should be minimum; 10 days is better), 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 subject to surface shrinkage cracking. The effects of drying can also be minimized by applying a sprayable curing compound at the end of the moist-curing period.

## CHAPTER 5—TESTING AND INSPECTION

### 5.1—Testing

**5.1.1** Tests on the fresh concrete sample should be conducted and specimens prepared in accordance with applicable ASTM Standards. Tests should be performed by an ACI certified concrete technician. The sample should be as representative as possible of the potential strength and other properties of the concrete as delivered. High temperature, low

relative humidity, and drying winds are particularly detrimental to the sample of fresh concrete used for making tests and molding specimens. Leaving the sample of fresh concrete exposed to sun, wind, or dry air will invalidate test results.

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

**5.1.3** The most important factor affecting plastic shrinkage is the evaporation rate, which can be estimated from Fig. 2.1.5 with the prevailing temperature, relative humidity, and wind speed. The evaporation rate can be determined more accurately by evaporating water from a cake pan having an area of approximately 1 ft<sup>2</sup> (0.093 m<sup>2</sup>). The pan is filled with water and the mass determined every 15 to 20 min to determine the evaporation rate, which is equal to the loss of water mass from the pan. A balance of at least 5.5 lb (2500 g) capacity is satisfactory.

**5.1.4** 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 in relation to most parts of the structure, test specimens are influenced more readily by changes in ambient temperatures. Extra effort is needed in hot weather to maintain strength test specimens at a temperature of 60 to 80 F (16 to 27 C) and to prevent moisture loss during the initial curing period, in accordance with ASTM C 31/C 31M. If possible, the specimens should be provided with an impervious cover and placed in a temperature-controlled job facility immediately after molding. If stored outside, exposure to the sun should be avoided and the cooling effect of evaporating water should be used to help provide the required curing condition. The following methods for nonpotentially absorptive test molds have been found practical:

- Embedding in damp sand. Care should be taken to maintain sand in continuously moist conditions (not to be used for cardboard molds);
- Covering with wet burlap. Care should be taken to maintain burlap in a continuously moist condition and out of contact with the concrete;
- Continuous fog sprays. Care should be taken to prevent interruptions of the fog spray; and
- Total immersion in water (not to be used for cardboard molds). Specimens may be immersed immediately in saturated limewater after molding. Because specimens are made with hydraulic cement, which hardens under water, specimen cylinders need not be covered with a cap, but generally they are, as a precautionary measure to prevent external damage.

**5.1.5** Molds must not be of a type that is potentially absorptive and expands when in contact with moisture or when immersed in water. Molds should meet the requirements of ASTM C 470. 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 also



be protected and handled carefully. They should then be stored in a moist condition at  $73 \pm 2$  F ( $23 \pm 1.7$  C) until the moment of test.

**5.1.6** Specimens in addition to those required for acceptance may be made and cured at the job site to assist in determining when forms can be removed, when shoring can be removed, and when the placement can be placed in service. Unless specimens used for these purposes are cured at the same place and as nearly as possible under the same conditions as the placement, results of the tests can be misleading. Alternative test methods for determining in place concrete strength are described in ASTM C 900 and ASTM C 918.

## 5.2—Inspection

**5.2.1** The numerous details to be looked after in concrete construction are covered in ACI 311.1R and 311.4R. The particular effects of hot weather on concrete performance and the precautions to be taken to minimize adverse effects have been discussed previously. Project inspection of concrete is necessary to ensure compliance with these additional precautions and procedures. Adequate inspection is also necessary to verify and document this compliance. The need for such measures as spraying of forms and subgrade, cooling concrete, providing sunshades, windscreens, or fogging and the like, and minimizing delays in placement and curing should be anticipated.

**5.2.2** Air temperature, concrete temperature (ASTM C 1064), general weather conditions (clear, cloudy), wind speed, relative humidity, and evaporation rate should be recorded at frequent intervals. 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:

- All water added to the mixture with corresponding mixing times;
- Time batched, time discharge started, and time discharge completed;
- Concrete temperature at time of delivery and after placing concrete;
- Observations on the appearance of concrete as delivered and after placing in forms;
- Slump of concrete as delivered;
- Slump of concrete as discharged; and
  - Protection and curing:
    - Method;
    - Time of application;
    - Rate of application;
    - Visual appearance of concrete; and
    - Duration of curing.

These observations should be included in the permanent project records.

## CHAPTER 6—REFERENCES

### 6.1—Referenced standards and reports

The documents of the various standards-producing organizations referred to in this document are listed below with their serial designation.

#### *American Concrete Institute*

- 116R Cement and Concrete Terminology
- 201.2R Guide to Durable Concrete
- 207.1R Mass Concrete
- 207.2R Effect of Restraint, Volume Change, and Reinforcement on Cracking of Massive Concrete
- 207.4R Cooling and Insulating Systems for Mass Concrete
- 211.1R Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete
- 211.2 Standard Practice for Selecting Proportions for Structural Lightweight Concrete
- 211R Guide for the Use of Normal Weight Aggregates in Concrete
- 212.3R Chemical Admixtures for Concrete
- 221R Guide for Use of Normal Weight Aggregates in Concrete
- 223R Standard Practice for the Use of Shrinkage-Compensating Concrete
- 224R Control of Cracking in Concrete Structures
- 224.3R Joints in Concrete Construction
- 225R Guide to the Selection and Use of Hydraulic Cements
- 226.3R Use of Fly Ash in Concrete
- 234R Guide for the Use of Silica Fume in Concrete
- 301 Specifications for Structural Concrete for Buildings
- 302.1R Guide for Concrete Floor and Slab Construction
- 304R Guide for Measuring, Mixing, Transporting, and Placing Concrete
- 306R Cold Weather Concreting
- 308R Standard Practice for Curing Concrete
- 309R Guide for Consolidation of Concrete
- 311.1R/ (SP-2) Manual of Concrete Inspection
- 311.4R Guide for Concrete Inspection Programs
- 318/ Building Code Requirements for Structural Concrete And Commentary
- 318M/ Building Code Requirements for Structural Concrete And Commentary
- 318RM Building Code Requirements for Structural Concrete And Commentary
- 363R State-of-the-Art Report on High Strength Concrete
- E4-96 Chemical and Air-Entraining Admixtures for Concrete

#### *ASTM*

- C 31/C 31M Standard Practice for Making and Curing Concrete Test Specimens in the Field
- C 156 Standard Test Method for Water Retention by Concrete Curing Materials
- C 172 Standard Practice for Sampling Freshly Mixed Concrete
- C 192 Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory
- C 309 Standard Specification for Liquid Membrane-Forming Compounds for Curing Concrete

- C 494 Standard Specification for Chemical Admixtures for Concrete
- C 595 Standard Specification for Blended Hydraulic Cements
- C 618 Standard Specification for Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Portland Cement Concrete
- C 989 Standard Specification for Ground Granulated Blast-Furnace Slag for Use in Concrete and Mortars
- C 1017 Standard Specification for Chemical Admixtures for Use in Producing Flowing Concrete
- C 1064 Standard Test Method for Temperature of Freshly Mixed Portland-Cement Concrete
- STP 169 C Significance of Tests and Properties of Concrete and Concrete-Making Materials, 1994, 571 pp.

These publications may be obtained from the following organizations:

American Concrete Institute  
P.O. Box 9094  
Farmington Hills, Mich. 48333-9094

ASTM  
100 Barr Harbor Drive  
West Conshohocken, Pa. 19428

## 6.2—Cited references

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## APPENDIX A—ESTIMATING CONCRETE TEMPERATURE

**A1—Equations for estimating temperature  $T$  of freshly mixed concrete are shown in the following.**

Without ice (in. – lb and SI units)

$$T = \frac{0.22(T_a W_a + T_c W_c) + T_w W_w + T_a W_{wa}}{0.22(W_a + W_c) + W_w + W_{wa}} \quad (\text{A-1})$$

With ice (in. – lb units)

$$T = \frac{0.22(T_a W_a + T_c W_c) + T_w W_w + T_a W_{wa} - 112 W_i}{0.22(W_a + W_c) + W_w + W_i + W_{wa}} \quad (\text{A-2})$$

With ice (SI units)

$$T = \frac{0.22(T_a W_a + T_c W_c) + T_w W_w + T_a W_{wa} - 79.6 W_i}{0.22(W_a + W_c) + W_w + W_i + W_{wa}} \quad (\text{A-3})$$

where

$T_a$  = temperature of aggregate

$T_c$  = temperature of cement

$T_w$  = temperature of batched mixing water from normal supply excluding ice

$T_i$  = temperature of ice. (Note: The temperature of free and absorbed water on the aggregate is assumed to be the same temperature as the aggregate. All temperatures are in F or C.)

$W_a$  = dry mass of aggregate

$W_c$  = mass of cement

$W_i$  = mass of ice

$W_w$  = mass of batched mixing water

$W_{wa}$  = mass of free and absorbed moisture in aggregate at  $T_a$ . (Note: All masses are in lb or kg.)

**A2—**Eq. (A-2) and (A-3), 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-4) or (A-5), which includes the temperature of the ice.

With ice (in. – lb units)

$$T = \frac{0.22(T_a W_a + T_c W_c) + T_w W_w}{0.22(W_a + W_c) + W_w + W_i + W_{wa} - 79.6 W_i} \quad (\text{A-4})$$

$$+ \frac{T_a W_{wa} - W_i(128 - 0.5 T_i)}{0.22(W_a + W_c) + W_w + W_i + W_{wa}}$$

With ice (SI units)

$$T = \frac{0.22(T_a W_a - T_c W_c) T_w W_w}{0.22(W_a + W_c) + W_w + W_i + W_{wa}} \quad (\text{A-5})$$

$$+ \frac{T_a W_{wa} - W_i(79.6 - 0.5 T_i)}{0.22(W_a + W_c) + W_w + W_i + W_{wa}}$$

## APPENDIX B—METHODS OF 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.

### B1—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 will depend upon 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 cost, this system appears to offer cooling at the lowest cost of available systems for cooling mixing water.

### B2—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 must 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 installation costs, 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 B4.

### B3—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 must 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. Costs of using block ice are: the cost 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 may also be produced and used as flake ice. This system requires a large capital investment.

#### **B4—Cooling mixed concrete with liquid nitrogen**

**B4.1** Injection of 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 less than 50 F. The method has been successfully used in a number of major concrete placements. The performance of concrete was not affected adversely by its exposure to large amounts of liquid nitrogen. Cost of this method is relatively high, but it may be justified on the basis of practical considerations and overall effectiveness.

**B4.2** Installations of the system consist 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 replen-

ishing 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<sup>3</sup> (48 m<sup>3</sup>) of liquid nitrogen will usually reduce concrete temperature 1 F (0.5 C).

#### **B5—Cooling of coarse aggregates**

**B5.1** 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 ±0.5 F (1 ±0.5C) will lower the final concrete temperature approximately 1 F (0.5 C). To use this method, the producer must 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 must be taken to evenly inundate the material so that slump variation from load to load is minimized.

**B5.2** Cooling of coarse aggregate can also be accomplished by blowing air through the moist aggregate. The air flow will enhance evaporative cooling and can bring the coarse aggregate temperature within 2 F (1 C) of wet bulb temperature. 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 cost.