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Guide to Hot Weather Concreting

Reported by ACI Committee 305

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Guide to Hot Weather Concreting

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Guide to Hot Weather Concreting

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

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

The materials, processes, quality control measures, and inspections described in this document should be tested, monitored, or performed as applicable only by individuals holding the appropriate ACI certifications or equivalent.

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

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CHAPTER 1—INTRODUCTION AND SCOPE**1.1—Introduction**

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

A maximum as-placed concrete temperature is often specified in an effort to control rate of setting, strength, durability, plastic shrinkage cracking, thermal cracking, and drying shrinkage. The placement of concrete in hot weather, however, is too complex to be dealt with by just setting a maximum as-placed or as-delivered concrete temperature. Concrete durability is defined as the ability of concrete to resist weathering action, chemical attack, abrasion, or any

other process of deterioration (ACI 201.2R). Generally, if concrete strengths are satisfactory and curing practices are sufficient to avoid undesirable drying of surfaces, the durability of hot weather concrete will not differ greatly from similar concrete placed at normal temperatures.

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

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

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

1.2—Scope

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

CHAPTER 2—NOTATION AND DEFINITIONS**2.1—Notation**

E = evaporation rate, lb/ft²/h (kg/m²/h)

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

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

e_s = saturation vapor pressure, psi (kPa)

r = relative humidity, percent

T = temperature, °F (°C)
 T_a = air temperature, °F (°C)
 T_c = concrete (water surface) temperature, °F (°C)
 V = average wind speed in mph (km/h), measured at 20 in. (0.5 m) above the concrete surface
 W = mass of water evaporated in lb/ft² (kg/m²) of water-covered surface per hour

2.2—Definitions

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

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

CHAPTER 3—POTENTIAL PROBLEMS AND PRACTICES

3.1—Potential problems in hot weather

Potential problems for concrete in the freshly mixed state include:

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

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

- a) Decreased strengths resulting from adding water to satisfy the higher water demand
- b) Increased tendency for drying shrinkage if additional water was added to the concrete
- c) Thermal cracking from either cooling of the overall structure, or from temperature differentials within the cross section of the member
- d) Decreased durability resulting from cracking
- e) Greater variability of surface appearance, such as cold joints or color differences, due to different rates of hydration or different water-cementitious materials ratios (w/cm)

3.2—Potential problems related to other factors

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

- a) Cements with different and increased rate of hydration
- b) High-early-strength concrete, which may be proportioned with higher total cementitious content
- c) Thin concrete sections with correspondingly greater percentages of steel, which may complicate placing and consolidation of concrete

- d) Economic necessity to continue work in extremely hot weather
- e) Use of shrinkage-compensating cement

3.3—Practices for hot weather concreting

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

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

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

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

- a) Selecting concrete materials and proportions with satisfactory records in hot weather conditions or that have shown by testing to be satisfactory
- b) Reducing and controlling the temperature of fresh concrete
- c) Using a concrete mixture with sufficient workability that will permit rapid placement and effective consolidation
- d) Minimizing the time to transport, place, consolidate, and finish the concrete
- e) Scheduling of placing operations during times of the day or night when weather conditions are favorable
- f) Protecting the concrete from moisture loss during placing and curing periods
- g) Scheduling a preplacement conference to discuss the requirements of hot weather concreting

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

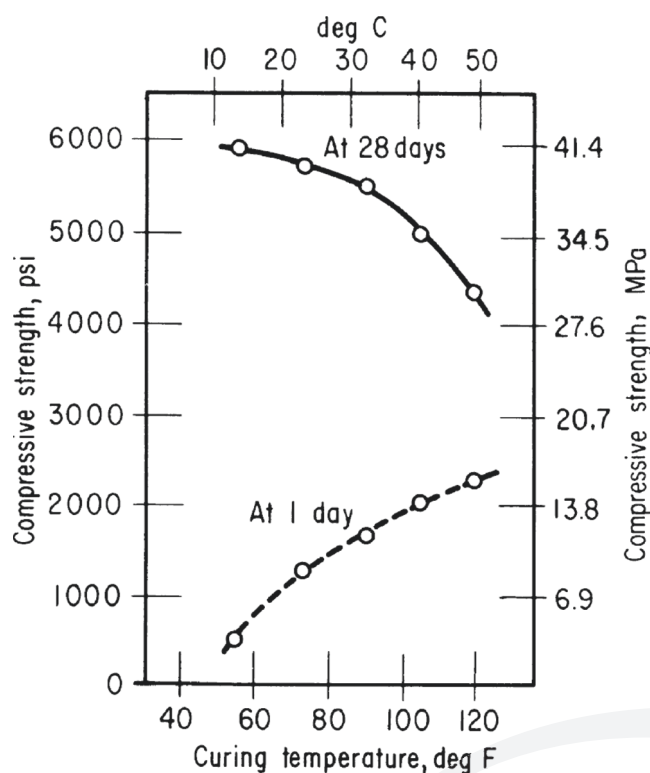


Fig. 4.1.1a—Effects of curing temperature on compressive strength of concrete (Verbeck and Helmuth 1968).

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

CHAPTER 4—EFFECTS OF HOT WEATHER ON CONCRETE PROPERTIES

4.1—General

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

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

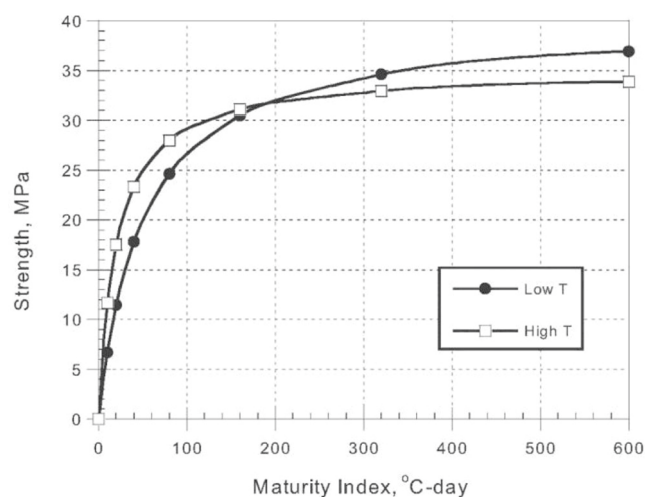


Fig. 4.1.1b—The crossover effect due to different early-age concrete temperature during development of the strength-maturity relationship (Carino and Lew 2001).

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

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

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

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

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

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

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

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

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

Figure 4.1.4 is the NRMCA-PCA nomograph that is based on common hydrological methods for estimating the rate of evaporation of water from lakes and reservoirs, and is therefore the most accurate when estimating the rate of evaporation from the surface of concrete while that surface is covered with bleed water. When the concrete surface is not covered with bleed water, the nomograph and its underlying mathematical expression tends to overestimate the actual rate of water loss from the concrete surface by as much as a factor of 2 or more (Al-Fadhala and Hover 2001). The method is therefore most useful in estimating the evaporation potential of the ambient conditions and not as an estimator of the actual rate of water loss from the concrete. Early in the bleeding process, however, and at rates of evaporation less than or equal to 0.2 lb/ft²/h (1.0 kg/m²/h), the method has been shown to be as accurate for bleed-water evaporation as for hydrological water-pan evaporation (Al-Fadhala and Hover 2001) as long as the temperature, humidity, and wind speed were measured as described in Fig. 4.1.4.

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

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

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

4.1.5 Effect of bleeding—When evaporation rate is expected to approach the bleeding rate of the concrete, precautions should be taken, as explained in detail in Chapter 6. Because bleeding rates vary from zero to over 0.2 lb/ft²/h (1.0 kg/m²/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/ft²/h (1.0 kg/m²/h). More recent experience with bridge deck overlays containing silica fume has led to specified allowable evaporation rates of only 0.05 lb/ft²/h (0.25 kg/m²/h) (Virginia Department of Transportation 1997; Krauss and Rogalla 1996). Construction specifications for New York and the City of Cincinnati assume intermediate

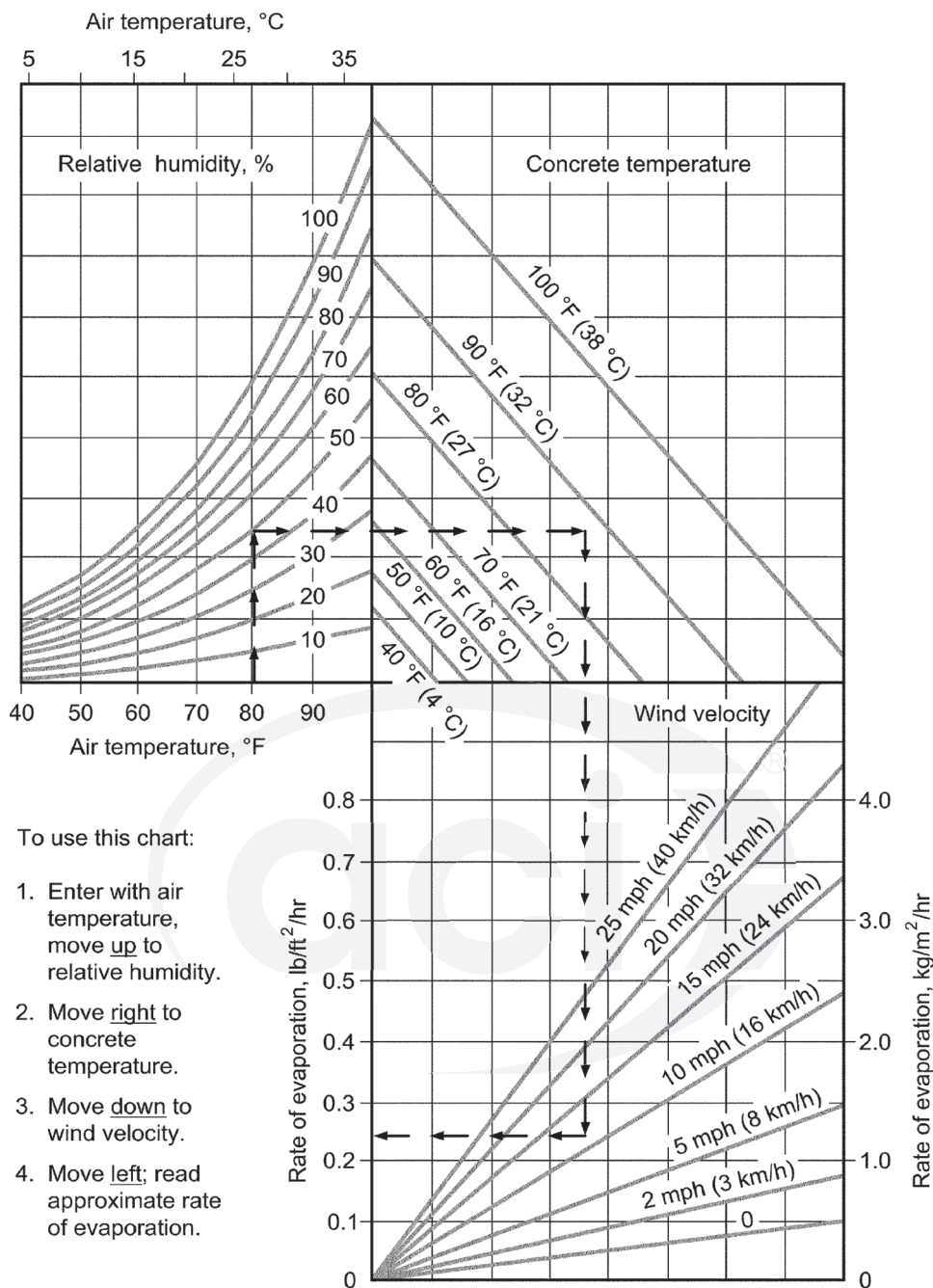


Fig. 4.1.4—Effect of concrete and air temperatures, relative humidity, and wind speed on the rate of evaporation of surface moisture from concrete. This chart provides a graphic method of estimating the loss of surface moisture for various weather conditions. To use this chart, follow the four steps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

evaporation rates of 0.15 and 0.10 lb/ft²/h (0.75 and 0.50 kg/m²/h), respectively. The probability for plastic shrinkage cracks to occur can be increased if the setting time of the concrete is delayed due to the use of slow-setting cement, an excessive dosage of retarding admixture, fly ash as a cement replacement, or cooled concrete. Fly ash is also likely to reduce bleeding and can thereby contribute to an increase

in cracking tendency (ACI 232.2R). In such instances, it is prudent to extend the time where countermeasures are employed to reduce evaporative conditions above the concrete. These countermeasures may include the use of monomolecular films when applied to the bleed-water layer for the purpose of delaying, fogging, windbreaks, shading, and others as discussed in subsequent sections herein.

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

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

4.2—Calculating estimated evaporation rate

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

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

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

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

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

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

When the combination of the temperatures of air and concrete, relative humidity, and wind speed has the capacity to evaporate water from a free water surface at a rate equal to

or greater than 0.2 lb/ft²/h (1.0 kg/m²/h), nearly all recently-cast concrete mixtures will be at risk of rapid, early drying and subsequent plastic shrinkage cracking. Under such conditions, this guide recommends that evaporation control measures are initiated. Many modern mixtures, particularly those proportioned for lower permeability, have a significantly reduced bleeding rate, and are consequently more vulnerable to plastic shrinkage cracking at lower evaporation rates. For such concretes, this guide considers the 0.2 lb/ft²/h (1.0 kg/m²/h) threshold to be unconservative.

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

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

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

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

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

$$W = 0.315(e_o - e_a)(0.253 + 0.060V) \quad (\text{SI})$$

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

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

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

$$e_s = 0.61 \cdot e^{\frac{17.3T}{23.3+T}} \quad (\text{SI})$$

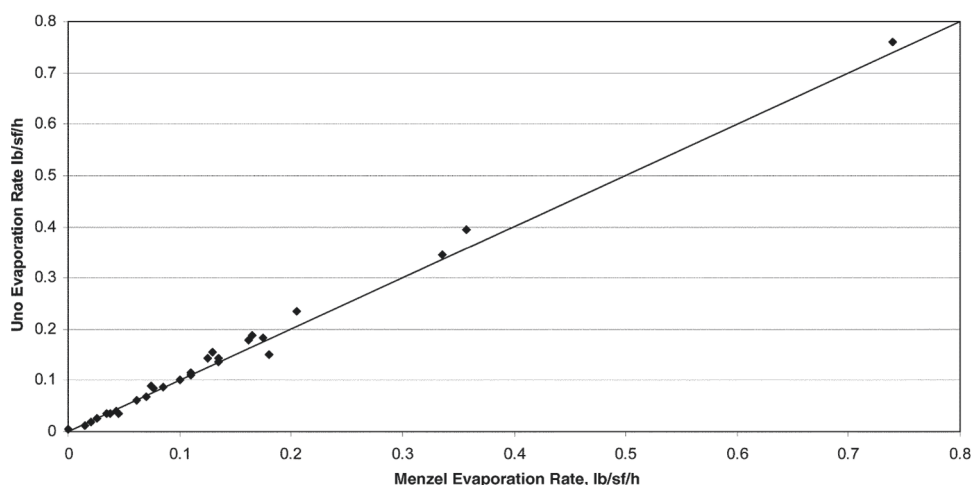


Fig. 4.2.2—Comparison of Menzel formula to Uno equation (Uno 1998).

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

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

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

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

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

Example (U.S. Customary units):

Given:

Concrete temperature (T_c) = 95°F

Air temperature (T_a) = 104°F

Wind speed (V) = 12 mph

Relative humidity (r) = 50 percent

Solve for evaporation rate (E)

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

$$E = (95^{2.5} - 0.5 \cdot 104^{2.5})(1 + 0.4 \cdot 12) \times 10^{-6} = 0.19 \text{ lb/ft}^2/\text{h}$$

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

Example (SI units):

Given:

Concrete temperature (T_c) = 35°C

Air temperature (T_a) = 40°C

Windspeed (V) = 20 km/h

Relative humidity (r) = 50 percent

Solve for evaporation rate (E)

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

$$E = 5[(35 + 18)^{2.5} - 0.5(40 + 18)^{2.5}](20 + 4) \times 10^{-6} = 0.92 \text{ kg/m}^2/\text{h}$$

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