

Title no. 95-M34

# Plastic Shrinkage Cracking and Evaporation Formulas



by Paul J. Uno

Freshly placed concrete exposed to hot, windy conditions is often prone to plastic shrinkage cracking (though other conditions can also promote this phenomenon). This type of cracking is normally noticed on slabs, pavements, beams, and generally other flat concrete surfaces. Many factors affect plastic shrinkage cracking, in particular the evaporation of water from the surface of freshly placed concrete. Other factors also influence the likelihood of plastic shrinkage cracking such as water-cement ratio, fines content, member size, admixtures, and on-site building practices. Evaporation itself is a function of climatic variables such as relative humidity, air temperature, the temperature of the evaporating surface, and very importantly the wind velocity at the surface.

This paper primarily explains the background to the evaporation nomograph found in ACI 305R-96, "Hot Weather Concreting" (Manual of Concrete Practice, Part 2-1996), where the graph provides a means of estimating the rate of evaporation of surface moisture from concrete. The paper offers an alternative nomograph and various formulas to predict an evaporation rate of surface water (primarily bleed water) from freshly placed concrete surfaces. Other factors related to evaporation and plastic shrinkage cracking are also addressed.

**Keywords:** air temperature; concrete temperature; cracks in concrete; durability; evaporation; high-strength concrete; hot weather concreting; humidity; plastic shrinkage; solar radiation; vapor pressure; wind.

## INTRODUCTION

Anyone associated with the concrete industry and confronted by hot weather problems has periodically used the ACI Hot Weather Concreting evaporation nomograph<sup>1</sup> (see Fig. 1). This graph provides a method of estimating the evaporation rate of bleed water from the surface of freshly placed concrete. The evaporation rate is calculated so as to give some indication of the possible onset of plastic shrinkage cracking.

The ACI report states: "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 whenever the evaporation rate is greater than the rate at which water rises to the surface of recently placed concrete by bleeding."

In 1992 the author began researching at a personal level the origin of the ACI nomograph and in particular the origin of "Menzel's formula" upon which the nomograph is based.

No references gave any clear indication of the "exact" origin of the formula. By 1995 the author had finally derived Menzel's formula, in particular the origin of the constants in the formula, then developed a simpler set of equations and a new nomograph which can be used in lieu of Menzel's formula or the ACI nomograph.

## RESEARCH SIGNIFICANCE

Plastic shrinkage cracking is a constant source of concern in the concrete industry. It causes anxiety between the concrete supplier and the client when cracks (albeit hairline) are observed on a recently placed concrete surface. It also causes concern to the designer as "long-term durability" comes into question. It is of particular concern in countries such as Australia, New Zealand, the U.S.A., South Africa, and the Middle East, where hot or windy conditions are experienced (though it is not restricted only to these countries or these climatic conditions).

New formulas and nomographs are offered, thus assisting the industry to more easily calculate the evaporation of water from a concrete surface and accordingly predict the possible onset of plastic shrinkage cracking. An explanation of the background to the ACI 305R-96 evaporation nomograph is given, thus helping researchers who have queried the basis of this graph, and in particular, its validity.

Finally, parameters such as water-cement ratio, admixtures, depth of section, fines content, fibers, and on-site building practices are reviewed in light of research done by others on their influence in promoting or resisting plastic shrinkage cracking.

## ACI NOMOGRAPH BACKGROUND

Since 1992 the evaporation nomograph (see Fig. 1) contained in the *ACI Manual of Concrete Practice*, Section

ACI Materials Journal, V. 95, No. 4, July-August 1998.  
Received September 11, 1996, and reviewed under Institute publication policies.  
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305R, “Hot Weather Concreting,”<sup>1</sup> has quoted Lerch as the reference for this chart, while prior to 1992 Bloem was quoted as the reference. In actual fact the nomograph was developed by Bloem and produced in a July 1960 paper<sup>2</sup> for the National Ready Mixed Concrete Association/National Sand and Gravel Association (NRMCA/NSGA). Many of the numerical values upon which the nomograph was formed were presented as a table in a paper for the *Journal* of the American Concrete Institute by Lerch<sup>3</sup> in Feb. 1957 and earlier in 1955 in a Portland Cement Association (PCA) paper.<sup>4</sup> The desirability to make this tabular information more easily available to ready-mix concrete producers (via a graphical method) was suggested to Bloem prior to 1960 by J. Monty Howard, engineer for the Dolese Company of Oklahoma City.

This evaporation table, however, was first published by Carl A. Menzel,<sup>5</sup> as outlined in a paper he wrote in 1954 for the PCA. The values in the table and those required to produce the Bloem nomograph were derived using Menzel’s formula, which is shown below as Eq. (1)

$$W = 0.44(e_o - e_a)(0.253 + 0.096V) \quad (1)$$

where

$W$  = weight (lb) of water evaporated per square foot of surface per hour (lb/ft<sup>2</sup>/hr),

$e_o$  = pressure of saturated vapor pressure at the temperature of the evaporating surface, psi,

$e_a$  = vapor pressure of air, psi, and

$V$  = average horizontal air or wind speed measured at a level about 20 in. higher than the evaporating surface, mph.

The ACI nomograph is still the preferred method for predicting the evaporation rate of bleed water from the surface of freshly placed concrete due to the difficulty in using Menzel’s equation. The Menzel formula requires the input of vapor pressure of air and the pressure of saturated vapor over the water surface of the concrete—both conditions being difficult to measure on site. It is interesting to note that in Menzel’s original paper he also presented an evaporation nomograph but it required the values of dewpoint to establish vapor pressures—again difficult parameters to measure or obtain generally. As mentioned in the introduction, the origin of Menzel’s formula, in particular the derivation of the constants in his formula, has not been apparent to many involved in concrete research and development.<sup>6,7</sup>

#### ORIGIN OF MENZEL’S FORMULA

Many researchers have questioned the applicability of Menzel’s formula under particular weather conditions, but as Mather<sup>8</sup> states, “The formula is valid regardless of whether the water surface from which the evaporation is taking place is a lake, pond, reservoir, pan, the bleed water layer over a

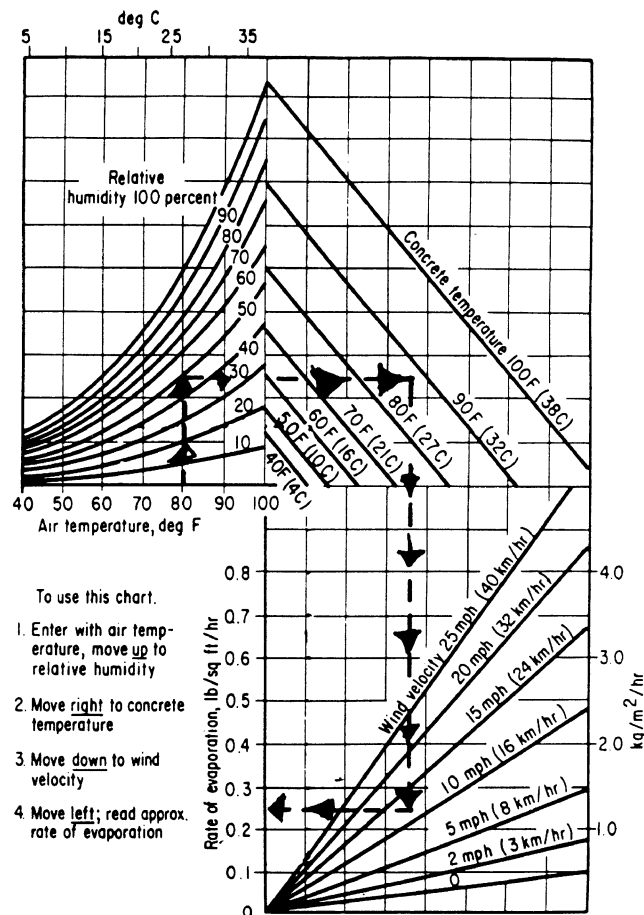


Fig. 1—ACI nomograph for estimating rate of evaporation of surface moisture from concrete<sup>1</sup>

slab of fresh concrete, or the layer of water over a hardened concrete surface covered by water.”

Menzel did not invent his formula since formulas of this type are merely adaptations of the standard form of evaporation formula outlined by Dalton<sup>9</sup> in 1802, namely

$$E = (e_o - e_a)f(u) \quad (2)$$

where

$E$  = evaporation rate,

$(e_o - e_a)$  = pressure difference, and

$f(u)$  = wind function.

While Dalton did not produce the standard formula above, he provided the scientific principles upon which this type of formula was based. However, if one refers to the many hundreds of books and papers written on evaporation and hydrology since that period, one will find many equations for predicting evaporation. So how did Menzel arrive at his formula?

In December 1948 various U.S. government bodies, including the Weather Bureau, decided to undertake research testing in the area of water loss from reservoirs. They ultimately carried out extensive water loss investigations at Lake Hefner between 1950 and 1952<sup>10,11</sup> measuring air temperatures, humidities, wind velocities, solar radiation, precipitation, pan evaporations, and pan water temperatures (using various pan types and sizes). One of the objectives of

these tests was to establish better correlations between pan evaporation and lake evaporation. It is from these Lake Hefner tests that Menzel derived his well-known formula.

The Lake Hefner tests were one of the most comprehensive series of water loss tests carried out up to this period (prior comprehensive tests of evaporation from free water surfaces were carried out by Rohwer<sup>12</sup> in 1931) and these tests carried out by researchers such as Kohler, Harbeck, and others produced many evaporation equations. One of the main evaporation formulas which developed from the Lake Hefner tests carried out by Kohler in the 1950 to 1952 period (and quoted in most hydrology texts to this date on this subject) is shown as Eq. (3) below

$$E = (e_o - e_a)^{0.88} (0.37 + 0.0041u) \quad (3)$$

where

$E$  = evaporation rate, in./day,

$u$  = wind velocity, miles/day, and

$(e_o - e_a)$  = pressure difference, in. Hg.

This was not the equation that Menzel used as this equation was based on the evaporation rates derived from the Standard Class A pan tests. These pans were 4 ft (122 cm) in diameter and 10 in. (25 cm) deep and supported on a wood frame above ground level. The test results from which Menzel derived his constants in Eq. (1) came from the Lake Hefner tests where the BPI (Bureau of Plant Industry) sunken pans had been used since these pans were of larger diameter (6 ft or 183 cm) and deeper (2 ft or 61 cm) than the Standard Class A pans and as such provided a better index. In fact the Lake Hefner report stated, "The physical characteristics of the BPI (sunken) pan seem to be most nearly representative of those of a natural body of water and therefore this pan merits high consideration on a theoretical basis."

Two standard forms of evaporation formula were quoted in the Lake Hefner report as "both being suitable for use" [see Eq. (4) and (5)]. The report stated, "Although these two equations appear almost quite different they fit observed data almost equally well because of the limited range of wind data." The two equations are shown below where  $a$ ,  $b$ ,  $c$ , and  $n$  are constants derived from tests and  $u$  is the wind velocity.

$$E = (e_o - e_a)(a + bu) \quad (4)$$

or

$$E = c(e_o - e_a)u^n \quad (5)$$

The constants  $a$  and  $b$  in Eq. (4) were determined by Kohler as 0.253 and 0.0040, respectively, with a correlation index of 0.91. Since  $u$  was in miles per day the conversion to mph meant the constant  $b$  now became 0.096. The pressure difference units were in inches of mercury (in. Hg) and so were converted to psi; similarly,  $E$  was in in./day and had to be converted to lb water/ft<sup>2</sup>/hr. These two last conversions resulted in a 0.44 factor being required at the beginning of

the formula. The Menzel equation for evaporation [shown earlier as Eq. (1)] finally became

$$E = 0.44 (e_o - e_a) (0.253 + 0.096V)$$

It can thus be seen that the formula quoted for many years as Menzel's formula was really an adaptation of Kohler's formula. Whichever formula is used, they all require the measurement of vapor pressures. As mentioned earlier, the Bloem nomograph resolved this problem in 1960 by using relative humidity and concrete water temperature as equivalent variables based upon standard psychrometric data (thus, the need for vapor pressures had been eliminated).

### NEW AND EASIER FORMULAS

Since the onset of calculators and computers the need for graphical systems has generally waned in favor of equations (albeit that the equations might be more complicated). This has resulted in attention being focussed back to Menzel's equation. As mentioned earlier the problem with his equation was the vapor pressure difference requirement. Many have developed equations which relate vapor pressure to relative humidity and temperature but most of these equations while very accurate are somewhat long and complicated.<sup>13,14</sup>

An easier and yet still very accurate equation which relates temperature and vapor pressure is one developed by Tetens<sup>15</sup> in 1930 as referenced by Murray,<sup>16</sup> Dilley,<sup>17</sup> and Mills.<sup>18</sup> It has been shown that Eq. (6) and (7) are accurate to within 0.001 percent for the temperature range 50 to 104 F (10 to 40 C). This equation (the metric form) is used by the World Meteorological Organization at the present.

#### In.-lb units

$$e_s = 0.0885 \exp \frac{17.3(T - 32)}{(T + 395.1)} \quad (6)$$

where

$e_s$  = saturation vapor pressure, psi, and

$T$  = temperature, F.

#### Metric units

$$e_s = 0.61 \exp \frac{17.3T}{(237.3 + T)} \quad (7)$$

where

$e_s$  = saturation vapor pressure, kPa, and

$T$  = temperature, C.

By merely substituting the air temperature and concrete (water) temperature into Eq. (6) or (7), one obtains the respective vapor pressures for air and the concrete water surface. These vapor pressures are then substituted into the modified version of Menzel's equation shown below

#### In.-lb units

$$E = 0.44(e_{so} - r.e_{sa})(0.253 + 0.096V) \quad (8)$$

where

$E$  = evaporation rate, lb/ft<sup>2</sup>/hr  
 $e_{so}$  = vapor pressure at concrete surface (psi) from Eq. (6)  
 $e_{sa}$  = vapor pressure of air (psi) from Eq. (6)  
 $r$  = (RH percent)/100  
 $V$  = wind velocity, mph

#### Metric units

$$E = 0.313(e_{so} - r \cdot e_{sa})(0.253 + 0.06V) \quad (9)$$

where

$E$  = evaporation rate, kg/m<sup>2</sup>/hr  
 $e_{so}$  = vapor pressure at concrete surface (kPa) from Eq. (7)  
 $e_{sa}$  = vapor pressure of air (kPa) from Eq. (7)  
 $r$  = (RH, percent)/100  
 $V$  = wind velocity, kph

#### Example 1

Air temperature  $T_a$  = 80 F (26.7 C)  
Conc. temperature  $T_c$  = 85 F (29.4 C)  
Relative humidity RH = 50 percent  
Wind velocity  $V$  = 20 mph (32 kph)

gives

Air vapor pressure  $e_{sa6}$  ( $e_{sa7}$ ) = 0.508 psi (3.51 kPa)  
Conc. vapor pressure  $e_{so6}$  ( $e_{so7}$ ) = 0.598 psi (4.11 kPa)

thus

Evaporation rate  $E_8$  ( $E_9$ ) = 0.329 lb/ft<sup>2</sup>/hr (1.60 kg/m<sup>2</sup>/hr)  
Evaporation rate  $E_{aci\ nomo}$  = 0.33 lb/ft<sup>2</sup>/hr (1.6 kg/m<sup>2</sup>/hr)

The author has developed a "single operation" equation (based upon Menzel's formula) which can be used on a simple hand-held calculator and which does not require vapor pressure precalculations. This is possible since a temperature-vapor pressure relationship, with a correlation coefficient of 0.99 for the temperature range 15 to 35 C (59 to 95 F), has already been incorporated into the equation. This formula is very appropriate for on-site quick checks to see if evaporation is going to be a critical factor in plastic shrinkage cracking. These simpler formulas are shown below as Eq. (10) and (11)

#### In.-lb units

$$E = (T_c^{2.5} - r \cdot T_a^{2.5})(1 + 0.4V) \times 10^{-6} \quad (10)$$

where

$E$  = evaporation rate, lb/ft<sup>2</sup>/hr,  
 $T_c$  = concrete (water surface) temperature, F,  
 $T_a$  = air temperature, F,  
 $r$  = (RH percent)/100, and  
 $V$  = wind velocity, mph.

#### Metric units

$$E = 5([T_c + 18]^{2.5} - r \cdot [T_a + 18]^{2.5})(V + 4) \times 10^{-6} \quad (11)$$

where

$E$  = evaporation rate, kg/m<sup>2</sup>/hr,  
 $T_c$  = concrete (water surface) temperature, C,  
 $T_a$  = air temperature, C,  
 $r$  = (RH percent)/100, and  
 $V$  = wind velocity, kph.

Using Example 1 again, the evaporation rates using Eq. (10) and (11) yield 0.342 lb/ft<sup>2</sup>/hr and 1.67 kg/m<sup>2</sup>/hr, respectively.

Table 1 shows a summary of the evaporation rates using all these formulas and compares them to Menzel's rates. As can be seen from the table, the calculated evaporation rates using the new formulas, i.e., Eq. (8) to (11), come very close in most cases to those rates derived using Menzel's equation and shown in the 1955 PCA publication and corresponding 1957 Lerch table.

The author has also produced a simpler nomograph for quickly estimating evaporation based upon the situation where the concrete temperature and the air temperature are the same (see Fig. 2)—an assumption that is often made when concrete temperatures are not available. If, however, a marked difference between air and concrete temperature does exist, then the ACI nomograph or the equations listed in this paper should be used.

## **ENVIRONMENTAL FACTORS**

As can be seen from the formulas the environmental factors that play a key role in evaporation are wind, air temperature, humidity, and water surface temperature. One factor that seems to have been overlooked when analyzing these formulas is solar radiation. It too plays a key role in the evaporation and plastic shrinkage cracking process and is accounted for in these formulas (as will be explained later). Let us address each of these environmental factors individually.

### **Evaporation**

This is the process by which a liquid is converted into a vapor or gas. This can happen where: a) heat energy is absorbed into the liquid, e.g. by solar radiation; or b) where the pressure above the liquid surface is less than that in the liquid, thus allowing the active water molecules to escape from the liquid as vapor.

This evaporation process is then accelerated if wind is present to continually remove escaping water molecules. The loss in energy from the evaporating water surface means that the temperature of the surface water decreases, thereby slowing down further evaporation.

### **Wind**

Wind is one of the most important considerations in controlling plastic shrinkage cracking. It can be measured or estimated in many ways, e.g., using anemometers, ventimeters, wind socks, and even observations of the surrounding elements. For precision, pressure tube anemometers or four and three cup anemometers can be used; however, if approximate wind speeds will suffice, then the Beaufort scale<sup>19</sup> can be adopted (see Table 2). This scale, first devised by Admiral Sir Francis Beaufort in 1805, has been used for many years to predict wind speed by making use of the movement of surrounding elements, e.g. trees, smoke, or waves. One problem

**Table 1—Comparisons of evaporated rates (based on the Menzel/Lerch format)**

Group	Condition	Case	Concrete temperature, C (F)	Air temperature, C (F)	Relative humidity, percent	Wind speed, kph (mph)	Evaporation Eq. (1) Menzel, kg/m <sup>2</sup> /hr (lb/ft <sup>2</sup> /hr)	Evaporation Eq. (9) [Eq. (8)] Uno, kg/m <sup>2</sup> /hr (lb/ft <sup>2</sup> /hr)	Evaporation Eq. (11) [Eq. (10)] Uno, kg/m <sup>2</sup> /hr (lb/ft <sup>2</sup> /hr)
1	Increase wind speed	1	21 (70)	21 (70)	70	0 (0)	0.07 (0.015)	0.06 (0.012)	0.06 (0.012)
		2				8 (5)	0.19 (0.038)	0.17 (0.035)	0.17 (0.036)
		3				16 (10)	0.30 (0.062)	0.28 (0.058)	0.28 (0.061)
		4				24 (15)	0.42 (0.085)	0.40 (0.081)	0.40 (0.086)
		5				32 (20)	0.54 (0.110)	0.51 (0.104)	0.51 (0.110)
		6				40 (25)	0.66 (0.135)	0.62 (0.127)	0.63 (0.135)
2	Decrease relative humidity	7	21 (70)	21 (70)	90	16 (10)	0.10 (0.020)	0.09 (0.019)	0.09 (0.20)
		8			70		0.30 (0.062)	0.28 (0.058)	0.28 (0.061)
		9			50		0.49 (0.100)	0.47 (0.097)	0.47 (0.102)
		10			30		0.66 (0.135)	0.66 (0.135)	0.66 (0.143)
		11			10		0.86 (0.175)	0.85 (0.174)	0.85 (0.184)
3	Increase concrete temperature and air temperature	12	10 (50)	10 (50)	70	16 (10)	0.13 (0.026)	0.14 (0.028)	0.12 (0.026)
		13	16 (60)	16 (60)			0.21 (0.043)	0.21 (0.041)	0.20 (0.041)
		14	21 (70)	21 (70)			0.30 (0.062)	0.28 (0.058)	0.28 (0.061)
		15	27 (80)	27 (80)			0.38 (0.077)	0.41 (0.081)	0.41 (0.085)
		16	32 (90)	32 (90)			0.54 (0.110)	0.54 (0.112)	0.53 (0.115)
		17	38 (100)	38 (100)			0.88 (0.180)	0.76 (0.152)	0.70 (0.150)
4	Decrease air temperature	18	21 (70)	27 (80)	70	16 (10)	0.00 (0.000)	0.00 (0.004)	0.00 (0.004)
		19		21 (70)			0.30 (0.062)	0.28 (0.058)	0.28 (0.061)
		20		10 (50)			0.60 (0.125)	0.62 (0.127)	0.66 (0.143)
		21		-1 (30)			0.81 (0.165)	0.79 (0.163)	0.87 (0.187)
5	Cold air high RH and wind	22	27 (80)	4 (40)	100	16 (10)	1.00 (0.205)	1.05 (0.206)	1.13 (0.235)
		23	21 (70)				0.63 (0.130)	0.64 (0.129)	0.72 (0.154)
		24	16 (60)				0.35 (0.075)	0.38 (0.072)	0.45 (0.088)
6	Cold air and variable wind	25	21 (70)	4 (40)	50	0 (0)	0.17 (0.035)	0.16 (0.033)	0.17 (0.035)
		26				16 (10)	0.79 (0.162)	0.79 (0.161)	0.84 (0.179)
		27				40 (25)	1.75 (0.357)	1.73 (0.353)	1.84 (0.395)
7	Average weather conditions	28	27 (80)	21 (70)	50	16 (10)	0.86 (0.175)	0.88 (0.174)	0.88 (0.183)
		29	21 (70)				0.49 (0.100)	0.47 (0.097)	0.47 (0.102)
		30	16 (60)				0.22 (0.045)	0.22 (0.039)	0.20 (0.036)
8	High concrete and air temperature + low RH	31	32 (90)	32 (90)	10	0	0.34 (0.070)	0.34 (0.070)	0.32 (0.069)
		32				16 (10)	1.64 (0.336)	1.63 (0.336)	1.60 (0.345)
		33				40 (25)	3.58 (0.740)	3.56 (0.735)	3.50 (0.760)

with using predetermined wind speed values is ascertaining the level at which the wind speeds were measured (since wind varies exponentially with height).

When the Lake Hefner tests were conducted using BPI pans, the top rim of these pans was located approximately 2 in. (50 mm) above the ground surface level. The anemometers used (three cup) for these same tests were mounted 6 in. (150 mm) above the rim of the Class A pans in the same test area. These Class A pans were 10 in. (250 mm) deep and mounted on a standard wooden platform such that the bottom of the Class A pan was 6 in. (150 mm) above the ground surface. From these values it can be seen that the anemometers recording the wind speeds for the Lake Hefner tests were located 20 in. (500 mm) above the top rim of the BPI pans. This is the height which Menzel quotes in his paper as being the height at which speeds should be recorded when using his equation stating “horizontal air or wind speed, ..., should

be measured at a level about 20 in. higher than the evaporating surface.”

Unfortunately, the ACI nomograph does not highlight this requirement for wind measurement and so appreciable error in calculated evaporation rates can be introduced if wind values are used based upon measurements taken at higher levels, e.g., Weather Bureau readings (taken at a height of 10 m [33 ft] in many countries). If, however, hand-held anemometers are used to determine wind speeds on site, then the difference should be negligible.

Kohler, in his book *Engineering Hydrology*,<sup>20</sup> quotes two formulas which address this issue. The more precise formula for converting wind speeds at different heights and from different surfaces is shown as Eq. (12). A simpler but slightly less accurate formula for converting wind speeds in the layer range 0 to 10 m (33 ft) is Eq. (13). These two models thus convert horizontal wind velocity at a datum level to wind velocity at a new height

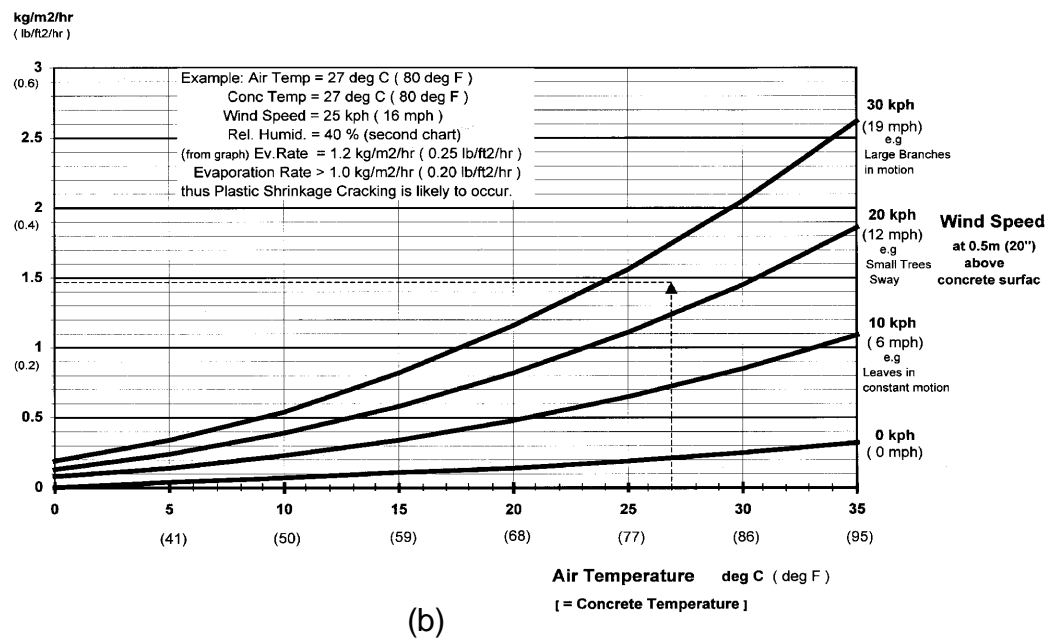
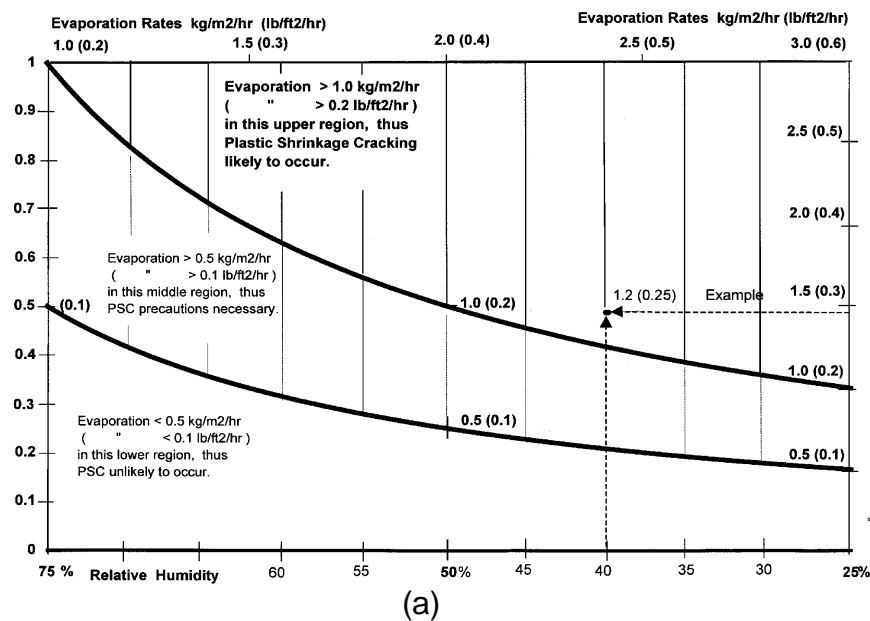


Fig. 2—Evaporation rates when air and concrete temperature are the same: (a) relative humidity; (b) air temperature vs. wind speed

$$\frac{V}{V_x} = \frac{\ln\left(\frac{z}{z_0} + 1\right)}{\ln\left(\frac{z_1}{z_0} + 1\right)} \quad (12)$$

or

$$V = V_x \times \left(\frac{z}{z_0}\right)^k \quad (13)$$

where

- V = resultant wind velocity at the new height required
- V<sub>x</sub> = wind velocity at the height measured
- z = new height required
- z<sub>o</sub> = roughness length
- z<sub>1</sub> = standard height
- k = constant

If we use the better wind model as shown by Eq.(12) where z<sub>o</sub> is taken as 0.001 cm (open water), z is 0.5 m (20 in.), and z<sub>1</sub> is 10 m (33 ft), this latter value being a standard height used by many Weather Bureaus around the world, we arrive at an equivalent wind velocity of 68 percent of the standard wind velocity at 10 m (33 ft).

If we use the approximate wind model shown by Eq. (13) where the standard value for the constant k is taken as 1/7, and z<sub>1</sub> is again 20 in. (0.5 m), the equivalent wind velocity we achieve this time is 65 percent of the standard wind velocity at 10 m (33 ft). It can thus be seen that a reasonable approximation for wind velocities to be used with Menzel's formula, the ACI nomograph or the author's equations, is represented by the simple expression shown as Eq. (14)

$$V_e = 2/3(V_{std}) \quad (14)$$

where

**Table 2—Modified Beaufort wind speed guide**

Beaufort no.	Description	Wind speed, knots	Wind speed $V_{std}$ at 30 ft, mph	Equivalent wind speed $V_e$ at 20 in., mph*	Wind speed $V_{std}$ at 10 m, kph	Equivalent wind speed $V_e$ at 0.5 m, kph*	On land	Wave height sea observed from coast, in. or ft (m)
0	Calm	< 1	< 1	< 1	< 1	< 1	Calm; smoke rises vertically	Sea like mirror, 0 in. (0)
1	Light air	1-3	1-3	1-2	1-5	1-3	Wind direction shown by smoke drift but not wind vanes	Ripples with the appearance of scales, 4 in. (0.1)
2	Light breeze	4-6	4-7	3-4	6-11	4-7	Wind felt on face; leaves rustle; ordinary vanes moved by wind	Small wavelets; crests do not break, 8 in. (0.2)
3	Gentle breeze	7-10	8-12	5-8	12-19	8-12	Leaves and small twigs in constant motion; wind extends light flag	Large wavelets; crests begin to break, 2 ft (0.6)
4	Moderate breeze	11-16	13-18	9-12	20-28	13-18	Raises dust and loose paper; small branches are moved	Small waves become longer, 3 ft (1)
5	Fresh breeze	17-21	19-24	13-16	29-38	19-25	Small trees in leaf begin to sway; crested wavelets form on inland waters	Many white horses formed, 6 ft (2)
6	Strong breeze	22-27	25-31	17-20	39-49	26-32	Large branches in motion; whistling heard in telegraph wires; umbrellas hard to use	Large waves, 10 ft. (3)

\* Equivalent wind speeds [as per Eq. (14)] to be used in evaporation equations

$V_e$  = equivalent wind velocity at 20 in. (0.5 m)  
 $V_{std}$  = wind velocity at the standard height of 10 m (33 ft)

When using Beaufort tables it is important to note that the wind speeds shown are at the standard height of 10 m (33 ft) above open flat ground.<sup>19</sup> The author has included an extra column (equivalent wind speeds) in the standard Beaufort table (see Table 2) based on Eq.(14) for use with the evaporation prediction methods nominated in this paper.

**Air temperature**

Measurement of this variable is quite straightforward and basically no different to the standard way in which most people would measure air temperature, the only provision being to measure away from the direct rays of the sun (thus minimizing the direct solar radiation component).

Air temperatures for the Lake Hefner tests were based on mean three hourly readings then averaged for the day. In all cases the measurements were recorded without direct sun on the air temperature instrumentation.

**Relative humidity**

Relative humidity is the ratio of the actual amount of moisture (lb/ft<sup>3</sup> or kg/m<sup>3</sup>) present in a unit volume of air to the amount of moisture (lb/ft<sup>3</sup> or kg/m<sup>3</sup>) the air could hold (saturation) at a particular temperature—normally expressed as a percentage. When relative humidity reaches 100 percent, evaporation normally ceases unless other forces (e.g. wind) replace the saturated air with nonsaturated air.

Relative humidity readings can be obtained by contacting the Weather Bureau or they can be recorded on site by means of a hand-held sling psychrometer or even a simple wet bulb/dry bulb thermometer.

**Concrete (water) temperature**

As explained earlier, it is really the temperature of the bleed (or surface) water that needs to be measured to establish the vapor pressure difference between the air and water

surface. Since it is difficult to measure the bleed water temperature, the concrete temperature is assumed to be at the same temperature as the bleed water above and so it is the concrete temperature that is measured. It would be difficult, however, to accurately assign a temperature component from any heat of hydration in the first few hours after placement.

**Solar radiation**

Solar radiation affects overlying air and land mass temperatures. It takes only 2.5 kJ (540 cal) of energy to convert one gm (<sup>1</sup>/<sub>28</sub> oz) of water from a liquid to a vapor and considering between 16 and 24 MJ of energy falls on each square meter of land mass in Australia on an average summer day (21 to 33 MJ, i.e., 20 to 31 thousand BTUs in the U.S.A.); evaporation (and subsequent precipitation) is a major function of solar radiation.

Although the ACI nomograph does not include solar radiation as a variable it is accounted for in Menzel’s equation since the Lake Hefner pans were exposed to direct and diffuse solar radiation for both clear and cloudy days during the two years of measurement. The solar contribution to evaporation was quantified by Kohler and others but required the measurement of solar radiation on site, e.g., by use of a pyrheliometer.

While many evaporation formulas have been quoted<sup>21</sup> over the past 100 years, they mainly fell into one of two approaches, those that were based upon “energy budget” principles (i.e., the inflow and outflow of energy which then influences the vaporization of water), and those that were based upon “aerodynamic” principles as outlined in this paper so far. The energy budget method takes into account the net radiation absorbed by the water and energy increase stored in the water, the latent heat of vaporization, and the ratio of heat loss by conduction to heat loss by evaporation (the Bowen Ratio). In 1948 Penman<sup>22</sup> successfully combined these two approaches to produce his well-known “combination” formula [Eq.(15)], namely

$$E = \left( \frac{Q_n \cdot \Delta + \gamma \cdot E_a}{(\Delta + \gamma)} \right) \quad (15)$$

where

$E$  = total evaporation,

$\Delta$  = slope of the saturation curve,

$$= \frac{4098 \cdot e_s}{(237.3 + T)^2},$$

$\gamma$  = psychrometric constant,

$$= 0.066 \text{ kPa/C},$$

$Q_n$  = solar radiation (see Ref. 20 for formula), and

$E_a$  = evaporation from aerodynamic formulas.

While this equation has the advantage of quantifying the contribution to evaporation by aerodynamic effects and solar radiation respectively, one drawback it has (besides having to record accurate radiation values) is that it is based on the premise that the water temperature and the air temperature are the same. This assumption, as Kohler states, "can result in an appreciable overestimation of evaporation under calm, humid conditions and a corresponding underestimate for dry, windy conditions."

The question remains, "Does the water evaporate faster or slower when exposed to direct 'clear sky' (i.e., more intense) radiation as opposed to diffuse 'cloudy sky' (i.e., less intense) radiation and does it hinder or help plastic shrinkage cracking?" Various researchers have expressed differing points of view in this area. Research by Hasanain et al.<sup>23</sup> indicated that shading concrete from direct, intense sun can reduce evaporation by as much as 50 percent. Tests on cement mortars by Ravina and Shalon<sup>24</sup> showed evaporation to be greatest when the samples were exposed to radiation. Van Dijk and Boardman<sup>25</sup> indicate that while radiation raises the temperature of the surface of the concrete and the rate of evaporation, it also induces accelerated hydration of the cement and thus strengthens the concrete surface. Due to this phenomenon, they indicate that slabs cast in the shade sometimes exhibit more cracking than slabs cast in the sun.

Having commented on the environmental factors which cause evaporation of bleed water, let us now address the bleeding rate of fresh concrete.

### BLEEDING RATE

The ACI report states that "precautions should be taken when the rate of evaporation is expected to approach 0.2 lb/ft<sup>2</sup>/hr (1.0 kg/m<sup>2</sup>/hr)." The Canadian Code<sup>26</sup> nominates 0.75 kg/m<sup>2</sup>/hr as the critical value while Australian references<sup>27</sup> quote 0.5 kg/m<sup>2</sup>/hr as a value at which precautions should be taken and a value of 1.0 kg/m<sup>2</sup>/hr as that value where plastic shrinkage cracking is likely to occur. The 0.2 lb/ft<sup>2</sup>/hr ACI figure first appeared in the July 1960 NRMCA article.<sup>2</sup> It appeared again in *Modern Concrete* (Oct. 1960) referenced as Technical Information Letter No. 171 for the NRMCA.<sup>28</sup> Both stated, "Data in literature suggest that concrete bleed rates for usual conditions of slab construction will lie in the range of about 0.1 to 0.3 lb/ft<sup>2</sup>/hr. Thus, when evaporation rate exceeds the lower of these figures, trouble with plastic cracking is potentially in the making. Conditions producing

evaporation of as much as 0.2 to 0.3 lb per sq ft per hour make the institution of precautionary measures almost mandatory." It is interesting to note that this evaporation range and the corresponding evaporation chart were not present in a 1967 version of the ACI "Hot Weather Concreting" report.

The author can only assume that since the value of 0.2 lb/ft<sup>2</sup>/hr (1.0 kg/m<sup>2</sup>/hr) first quoted in 1960 was based upon "data in literature ..." and that one of the most thorough research programs producing data which addressed concrete bleeding was carried out by Powers<sup>29</sup> in 1939 at the Portland Cement Association, that it is from this latter source that the 0.2 lb/ft<sup>2</sup>/hr figure first originated.

Work by Powers resulted in bleeding rates in the range of  $32 \times 10^{-6}$  to  $113 \times 10^{-6}$  cm/sec which equates to 0.24 to 0.83 lb/ft<sup>2</sup>/hr (1.15 to 4.1 kg/m<sup>2</sup>/hr). It is thus more than likely that a lower bound figure of approximately 0.2 was adopted as this bleed rate would be the most critical for high evaporation conditions. In his 1968 publication *Properties of Concrete*,<sup>30</sup> Powers included the Menzel/Lerch evaporation table and stated, "Bleeding among different mixes made with the same materials may range from  $20 \times 10^{-6}$  to  $100 \times 10^{-6}$  cm/sec depending upon the cement content. In all cases the period of constant rate lasts 15 to 30 minutes at the most and thereafter the rate diminishes, reaching zero within an hour and a half. Thus we see that there are very few atmospheric conditions under which the rate of evaporation may not exceed the rate of bleeding before which settlement is completed." The  $20 \times 10^{-6}$  cm/sec rate he nominated converts to 0.15 lb/ft<sup>2</sup>/hr or 0.72 kg/m<sup>2</sup>/hr—similar to the Canadian limit.

### PLASTIC SHRINKAGE CRACKING

In 1942 Swayse<sup>31</sup> defined plastic shrinkage as "a volumetric contraction of cement paste (the magnitude of this contraction being of the order of 1 percent of the absolute volume of the dry cement)" whereas today the ACI defines it as "shrinkage that takes place before cement paste, mortar, grout, or concrete sets." Plastic shrinkage cracking is thus the cracking that develops primarily in the top surface of the freshly laid (plastic) concrete due to this volumetric contraction of the cement paste which is accelerated by loss of surface bleed water via evaporation.

Freshly placed concrete sometimes does not have sufficient time to develop enough tensile strength to resist contraction stresses induced in capillary pores<sup>32</sup> by rapid evaporation; thus cracks can develop throughout the top surface of the concrete. These cracks are normally parallel and only in the surface of the concrete; however, there can be cases where they extend totally through the slab (aggravated by drying shrinkage) and can also be random in appearance. It is interesting to note, however, that research by Ravina and Shalon<sup>24</sup> in 1968 did indicate that cracking can still occur even when evaporation is negligible (in particular when thermal strain exceeds concrete strain capacity).

There are a whole range of other factors which influence plastic shrinkage cracking (other than evaporation rate). We will now address each of these in turn.



## OTHER FACTORS INFLUENCING PLASTIC SHRINKAGE CRACKING

Factors relating to the properties of the fresh concrete, on-site concrete practices, and other variables which have an influence on plastic shrinkage cracking have been listed below and are subsequently addressed individually. They include

- concrete strength (related to the total cement or binder content)
- depth of concrete section (related to the bleeding capacity)
- finer content (related to water demand)
- plastic state of the mix (i.e., semi-plastic, plastic, wet)
- admixtures (primarily retarders)
- fibers (primarily nylon or polypropylene)
- sub-base preparation (primarily sub-base membranes)
- surface sprays (primarily aliphatic alcohols)

### Concrete strength

Use of the ACI "single value" critical evaporation rate has been questioned by many researchers over the years. Recent research by Samman, Mirza, and Wafa<sup>33</sup> highlight the problems associated with only using the 0.2 lb/ft<sup>2</sup>/hr (1.0 kg/m<sup>2</sup>/hr) evaporation rate. Their research showed that high-strength concrete mixes containing high proportions of cement (with and without silica fume) produced concretes with low bleed rates and subsequently high susceptibility to plastic shrinkage cracking. Other research<sup>34</sup> of a similar nature has been performed with cement mortars, though cement mortars would be more prone to plastic shrinkage cracking than concretes due to the greater paste content per unit volume.

The author has plotted the results of the Samman et al. tests in a different form to that originally illustrated in their paper by comparing concrete strength, evaporation rate, and crack area all in the one diagram (see Fig. 3). A straight line was produced to approximate the commencement of surface cracking for the various strengths of concrete with Eq. (16) and (17), providing a means of relating concrete strength and evaporation for the Samman tests.

#### Metric units

$$E_{max} = 1.6 - 0.016f_c \quad (16)$$

where

$E_{max}$  = max allowable evaporation rate, kg/m<sup>2</sup>/hr, and  
 $f_c$  = strength of concrete, MPa.

#### In.-lb units

$$E_{max} = 0.33 - 22.6 \times 10^{-6} f_c \quad (17)$$

where

$E_{max}$  = max allowable evaporation rate, lb/ft<sup>2</sup>/hr, and  
 $f_c$  = strength of concrete, psi.

While Eq.(16) and (17) are based only on the few tests carried out by Samman et al., the author believes an equation of this form addressing the concrete strength (or  $w/c$  ratio) versus evaporation relationship should be present in the ACI recommendations rather than the "single figure" approach.

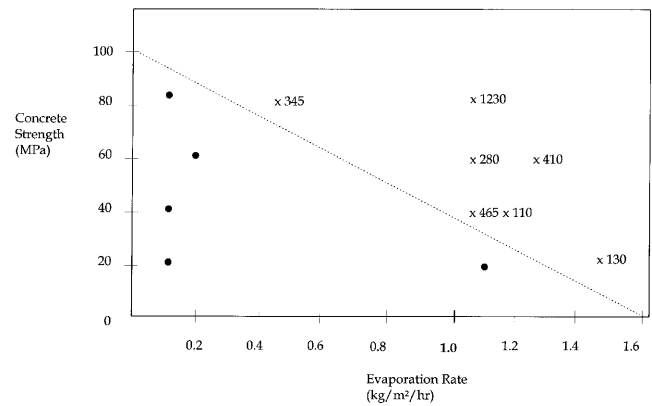


Fig. 3—Concrete strength and evaporation rate compared with crack area (adapted from Ref. 33) (“•” indicates zero plastic shrinkage crack area; “x” indicates crack areas in mm<sup>2</sup> shown above dotted lines)

### Depth of section

The depth of section determines the bleed capacity of the concrete since a deeper section will contain more solids to settle and correspondingly more bleed water to rise to the surface (see Van Dijk<sup>25</sup>). Research by Schiessl and Schmidt<sup>35</sup> in 1990 demonstrated the linear relationship between total bleeding capacity and the bleeding rate.

This depth factor more often has an effect on plastic “settlement” cracking (i.e., cracks formed over reinforcement or large aggregate); however, in light of the ability of a deeper section to produce bleed water supply to the concrete surface over a longer period, this should tend to resist the premature onset of cracks. Kral and Gebauer<sup>36</sup> found the critical evaporation period was between two and 4<sup>1/2</sup> hr after casting when combined with high winds (not the first hour or two as usually thought). This would imply that deeper sections should be less prone to plastic shrinkage cracking (however, more prone to plastic settlement cracking).

### Fines content

The high proportions of fine aggregate, special cements (e.g. low heat cements), or fine supplementary cementitious materials (e.g. fly ash, slag, and silica fume) in some concretes would tend to reduce the bleed rate of concretes by mere fact of the greater surface area presented to the mixing water volume. Add to this the fact that these materials do not contribute significant strength gain in the very short term would imply that these concretes should warrant special precautions at lower rates of evaporation.

### Plastic state

The research by Ravina and Shalon<sup>24</sup> mentioned earlier on cement mortar samples also concluded that plastic shrinkage cracking was worst for the wet and plastic mortars (where  $w/c$  ratios were 0.7 and 0.5 respectively) yet least for the semi-plastic mortars ( $w/c$  ratio of 0.6). This differs, however, from the findings of Wittman<sup>32</sup> where the critical plastic state for maximum cracking was nominated at a  $w/c$  ratio of 0.52 with lower or higher  $w/c$  ratios being less prone to plastic shrinkage cracking. Tests on 104 concrete samples by Kral and Gebauer<sup>36</sup> confirmed that extremely dry or extremely fluid mixes were less susceptible to shrinkage cracking.

## Admixtures

The concretes of today, while not that unlike those in the 40s and 50s, do on many occasions have a variety of admixtures introduced into the mix which have an influence on plastic shrinkage cracking. The use of water-reducing agents (water reducers), high-range water-reducing agents (superplasticizers), accelerating and retarding agents (accelerators and retarders), and oxides all affect the plastic state of the concrete in some manner. Research by Cabrera<sup>37</sup> indicates that concretes containing superplasticizers, while bleeding less, tend to resist or prolong the onset of plastic shrinkage cracking due to the modification in concrete surface tension. Research generally has shown that excess use of retarding admixtures can make freshly placed concrete more susceptible to plastic shrinkage cracking due to the slower set and strength gain of the mix.<sup>38</sup> In relation to water-reducing admixtures, oxides, and accelerating admixtures, the use of a water-reducing admixture would affect the plastic state of the concrete and so would have to be addressed as per the comments in the section on plastic state; oxides relate to the fines content of a mix and so the section on Fines concrete would apply; while accelerators hasten set and so should decrease the likelihood of cracking.

## Fibers

The use of fibers in concrete over the past few years has resulted in much research<sup>39,40</sup> being carried out in this area, in particular with polypropylene fibers. The general consensus is that polypropylene fibers do provide some improvement to reducing the onset of plastic shrinkage cracking by holding or stitching the plastic concrete surface together, thus minimizing the formation of early microcracks. One point to note is that the introduction of fibers can reduce the bleed rate of the concrete via the increased fiber surface area introduced into the mix. This can in some cases result in concrete placers adding more water to the mix to make it more workable, thereby reducing the concrete strength accordingly.

## Sub-base preparation

The sub-base materials under a concrete slab have also been shown to have a definite effect on plastic shrinkage cracking (and longer term drying shrinkage cracking). Tests carried out by Campbell et al.<sup>41</sup> using three sub-base conditions, plastic sheeting (polyethylene), sand, and sand-cement mix respectively, showed that extensive cracking only developed on exterior concrete slabs with plastic sheeting underneath; however, Turton<sup>42</sup> disputes this phenomenon based upon his observations in the U.K.

## Surface sprays

Tests carried out in the U.S. by Koberg and others<sup>43</sup> between 1959 and 1960 looked at the suppression of evaporation control from lakes and reservoirs by the use of monomolecular films (alkanols). This research stemmed from earlier tests done in Australia in 1952 by Mansfield where field testing of monolayers reported evaporation reductions in the order of 30 percent. Subsequent testing done in 1965 at Utah University<sup>44</sup> confirmed that evaporation of bleed water could also be suppressed by the application of

aliphatic alcohols with reductions in evaporation of 75 percent achieved.

To summarize the standard precautions for minimizing the onset of plastic shrinkage cracking:

- a) Use wind breaks to reduce the air flow over the top surface of the concrete.
- b) Use evaporative retarders such as aliphatic alcohols.
- c) Consider the use of fibers.
- d) Address the fines content in the mix.
- e) Avoid admixtures that reduce bleed rate (without some improved surface tension).
- f) Avoid the excess use of retarders.
- g) Determine if plastic membranes under slabs are required (e.g., to stop rising damp).

It is interesting to note that while plastic shrinkage cracking and evaporation are phenomena the concrete industry has tried to minimize as outlined in this paper, extensive work by Jaegermann and Glucklich<sup>45</sup> concluded that high evaporation soon after casting generally resulted in denser better quality long-term concrete (albeit that some internal cracks existed). They did indicate, however, that proper curing would have to be provided.

## CONCLUSIONS AND RECOMMENDATIONS

Plastic shrinkage is normally associated with concrete slab problems—primarily plastic shrinkage cracking.

Researchers such as Menzel, Lerch, Bloem, Powers, and others were instrumental in providing methods for predicting the likelihood of plastic shrinkage cracking due to evaporation and concrete bleeding. The author has provided some further formulas, a simpler nomograph, and a set of guidelines which should assist the cement and concrete industry in minimizing the onset of plastic shrinkage cracking.

The author believes that the “single figure” criterion for deeming a critical evaporation rate needs to be addressed in light of the factors outlined in this paper, in particular the concrete strength (or *w/c* ratio) aspect.

While it is encouraging that researchers in the area of plastic shrinkage cracking seem to have adopted a standard method for testing slabs (i.e., the method proposed by Kraai<sup>46</sup> in 1985), the author feels that more research needs to be carried out on thicker concrete specimens, i.e., more indicative of the typical slabs on building sites, e.g. 100 to 150 mm (4 to 6 in.). In conjunction with this, the concretes used in these tests should reflect the types of mixes that are becoming more commonplace in the market, i.e., mixes containing water reducers, fly ash, slag, silica fume, plasticizers, and so on, thus gaining a better understanding of how the parameters outlined in the latter part of this paper affect plastic shrinkage cracking.

## CONVERSION FACTORS

1 m	=	39.37 in.
1 kph	=	0.621 mph
1 kg	=	2.204 lb
1 kg/m <sup>2</sup> /hr	=	0.205 lb/ft <sup>2</sup> /hr
1 kPa	=	0.145 psi
1 MJ	=	947.8 BTU
1 C	=	5/9 (F - 32)

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